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Technology Utilization Division

EFFECTS OF LOW TEMPERATURES on STRUCTURAL METALS

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Foreword

The Administrator of the National Aeronautics and Space Administration has established a Technology Utilization Program for "the rapid dissemination of information . . . on technological developments . . . which appear to be useful for general industrial application." From a variety of sources, such as NASA Research Centers and NASA contractors, space-related technology is screened and that which has potential industrial use is made generally available. Thus American industry will receive information from the nation's space program about the latest developments in operating techniques, management systems, materials, processes, structures, and analytical and design procedures in numerous technical fields.

This publication is part of a series designed to provide this technical information. It is based on data developed during a continuing series of inhouse and contractor research studies on the properties of materials at low temperatures by the Marshall Space Flight Center, Propulsion and Vehicle Engineering Laboratory, Dr. W. R. Lucas, Chief, Materials Division.

The report was prepared by H. L. Martin of the MSFC Technology Utilization Office in cooperation with A. G. Imgram and W. S. Lyman of the Battelle Memorial Institute, under Contract No. NASr–100(02).

THE DIRECTOR, *Technology Utilization Division*
National Aeronautics and Space Administration

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Introduction

The advanced liquid-propellant rockets for the exploration of space use liquefied gases as part of the fuel mixture. The Atlas and Titan ICBM's and the Saturn booster employ liquid oxygen as an oxidizing agent, and liquid-hydrogen rocket engines are being developed for the upper stages in the Saturn booster system. Oxygen and hydrogen are an efficient combination of oxidizer and fuel, if they can be employed in the liquid state. In order to maintain these reactants as liquids, they must be stored at or below their boiling temperatures (−297° F for oxygen and −423° F for hydrogen at normal atmospheric pressure). There are many problems, associated with the storage and handling of these cryogenic fluids, which must be considered in the design and fabrication of tankage and other components of such systems. Thus, a continuing program is being conducted by the Propulsion and Vehicle Engineering Laboratory of the Marshall Space Flight Center to evaluate the applicability of various metallic materials at cryogenic temperatures.

The severest limitation on the use of certain metals at low temperatures is that imposed by the increasing susceptibility to brittle failure as the temperature decreases. Just as with materials used for any other structural purposes, strength, ductility, and toughness are important considerations in most cryogenic applications. The studies at the Marshall Space Flight Center have emphasized these aspects of materials behavior in evaluating the mechanical properties of the materials discussed in this review.

Industrial Applications

The most dramatic use of cryogenic technology is surely in the aerospace industry. However, numerous other concepts, totally unrelated to the aerospace effort, are being developed or employed that involve the storage and handling of cryogenic fluids. Only a few of the more predominant or interesting of these concepts are described below.

1. Liquid nitrogen (boiling point −320° F) is commonly used for the quick freezing of foods. Furthermore, liquid nitrogen refrigeration systems are sure to gain more widespread use in the transportation and preservation of agricultural products. These systems will permit better temperature control, and will require less maintenance than conventional systems.

2. Other uses of cryogenic liquid include the stiffening of rubber for precise machining and the cryogenic forming of metals to achieve high strengths.

3. The increasing development of superconductors for electric motors, generators transformers, and magnets will greatly enlarge the consumption of cryogenic liquids by the electrical industry. This use of superconductors will reduce the electrical power requirements of these devices.

4. In the medical sciences, it is expected that the use of cryogenic liquids for the preservation of blood will be expanded. The preservation of whole organs, and even entire living animals, by quick freezing may also become a reality. In addition, bloodless surgery, made possible by circulating liquid nitrogen through a scalpel, is being studied.

5. Liquefaction of natural gas is a great aid in increasing the utilization of the world's natural gas reserves. Intercontinental transportation of natural gas by pipe line is often impractical. Consequently, most of the valuable natural gas occurring as a by-product when oil fields are exploited has been wasted. Lique-

faction of the gas enables its transportation in tank cars and ocean-going ships, and special tankers have been built to transport liquefied methane, propane, and butane. Cryogenic storage facilities have been constructed at various terminals where the liquefied gas is loaded and unloaded from such tankers.

Thus, it is evident that cryogenic engineering is destined to become an increasingly important aspect of industrial technology. The extensive experience in cryogenic engineering resulting from the aerospace effort is a most important asset to the early and efficient integration of cryogenic technology into private industry. It is with this in mind that this report is published describing the Marshall Space Flight Center's program for testing and evaluation of numerous cryogenic structural materials.

Properties at Low Temperatures—Background Information

The trends in the effects of low temperatures on the mechanical properties of metals can be generalized to some extent. These trends and the important features of cryogenic testing are discussed in this section.

Certain metals show a marked decrease in ductility (i.e., elongation and reduction in area) with decreasing temperature over a relatively narrow temperature range. The extent to which the ductility is lowered by decreasing temperature depends to a large extent on the crystal structure of the metal.

Metals with body-centered cubic (BCC) crystal structures (e.g., iron, chromium, columbium, molybdenum, and tungsten) are generally severely embrittled at low temperatures. Ductilities drop to practically zero, and fractures occur without any prior indication at stress levels below accepted design values.

Shortly after the beginning of this century, Ludwick (ref. 1) proposed the relationships schematically illustrated in figure 1 to describe the ductility transition of BCC metals. Although many advances have been made in understanding the atomistic mechanisms of brittle crack nucleation and propagation, the basic Ludwick diagram gives a good approach to the engineering aspects of the ductility transition problem. Figure 1 illustrates: (1) the marked increase in yield strength with decreasing temperature at low temperatures, and (2) the relative insensitivity of the fracture stress to temperature. It is easily visualized that plastic deformation cannot precede fracture at temperatures below the temperature (T_1) at which the yield strength equals the fracture strength. Consequently, at temperatures below T_1, BCC metals do not display any measurable ductility.

The unalloyed face-centered cubic (FCC) metals copper and nickel differ from BCC metals in that their yield strengths are not greatly increased at low temperatures, and they retain considerable ductility at low temperatures.

Aluminum, also an FCC metal, increases in yield strength at low temperatures, with no loss in ductility. Many aluminum alloys display similar characteristics, that is, increasing yield strength with no reduction in ductility at low temperatures.

Unalloyed metals with a hexagonal close-packed (HCP) structure (e.g., titanium, magnesium, and beryllium) behave similarly to FCC metals at low temperatures.

Most structural elements and shapes are not ideally smooth and homogenous; they may contain various inherent or "built-in" discontinuities such as microstructural inclusions or voids, cracks, scratches, sharp fillets, notches, and holes. These act as "stress concentrators" that locally decrease the ratio of maximum operative shear stress to applied tensile stress (normally 0.5 under uniaxial loading conditions). Since plastic deformation is dependent only on the operative shear stress, the applied tensile stress required to initiate yielding (yield strength) is increased. However, brittle fracture is governed mainly by the applied normal or tensile stress. Therefore, the fracture stress as such is unaffected by the presence of a notch. The net result is that the yield-strength curve in figure 1 is raised in relation to the fracture-stress curve. (See ref. 1.) With BCC metals this means that the yield-strength curve intersects the fracture-stress curve at higher temperatures. Thus defects tend to cause failure at higher temperatures than would be predicted by the unnotched tensile test. With FCC and HCP metals, defects may similarly cause the yield-strength curve to intersect the fracture-stress curve, resulting in brittle failure, despite the absence of brittle failure in unnotched specimens.

Notches also increase the stress at the root of the notch above the nominal calculated value depending on the notch severity. One means of indicating the notch severity is by the stress concentration factor, K_t. However, the stress decreases rapidly and nearly equals the nominal value a short distance away from the point of maximum stress amplification (ref. 2). This local stress magnification causes the propagation of brittle cracks nucleated near the notch defect.

Notched tensile specimens are commonly tested to evaluate the effect of stress raisers on the behavior of the metals. Notched-unnotched strength ratios below 1.0 indicate that the material is weakened by the presence of defects. From an engineering point of view, some ductility as measured in the unnotched tensile test is needed to minimize the occurrence of notch embrittlement by allowing the material to flow locally and reduce the severity of the stress concentration. The less "reserve ductility" available, the more likely the chances that defects will cause brittle fractures. However, the ductility as measured by elongation is not proportional to the fracture toughness of the material at the given testing temperature.

The foregoing has been concerned primarily with unalloyed metals. Although the same concepts can be applied to the more complex engineering alloys, the effects of various alloying elements upon phase relationships and microstructure must also be considered. Alloying elements added in solid solution to increase the strength, generally lower the ductility, and/or raise the ductility transition temperature as well. This is probably attributable either to an increase in the yield strength in relation to the fracture stress in the Ludwick diagram, or an increase in the work-hardening rate that permits the fracture stress to be attained at lower total strains.

The influence of alloying elements on phase relationships is probably of even greater consequence with alloy bases that can undergo an allotropic transformation. Stabilization of an allotropic form of the base metal may result in behavior totally different from that normally observed. For example, nickel additions to iron stabilize iron's FCC austenite phase and thus eliminate the ductility transition normally observed with the BCC ferrite phase present in low-alloy steels. On the other hand, chromium and vanadium additions stabilize the BCC beta phase of titanium, and thereby degrade the excellent low temperature properties of HCP alpha titanium.

The effect of alloying additions that form intermetallic or interstitial compounds is somewhat more complex. Dispersed, second-phase particles located within individual grains can lower the ductility. Furthermore, similar to solid-solution additions, they may lower ductility by increasing the yield strength in relation to the fracture strength or by increasing the work-hardening rate. However, they also effectively increase the fineness of the microstructure which is conducive to high ductility.

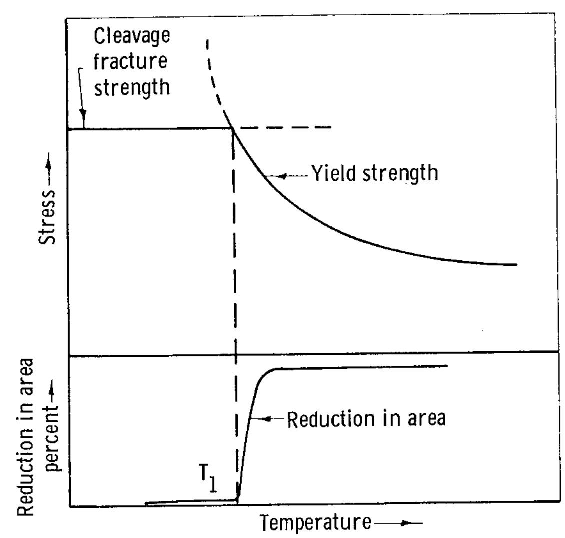

FIGURE 1.—Schematic relationship of yield strength and ductile-to-brittle transition temperature (ref. 1).

Contrary to the varying effects of dispersed particles within grains, second-phase particles in grain boundaries are always detrimental to ductility, especially if they form a continuous network. Residual, impurity elements that segregate in and form a second phase in the grain boundaries always have a marked effect on the toughness.

The influence of alloying elements should be considered from the standpoint of increasing temperature T_1 in the Ludwick diagram. Significant decreases in the residual ductility resulting from the alloy additions may result in embrittlement in the presence of defects.

The effect of welding on ductility should be examined from both the development of a cast structure in the fusion zone and the influence of thermal exposure on the microstructure in the adjacent heat-affected zones. Cast structures are generally characterized by a rather high concentration of defects such as porosity and large second-phase particles or nonmetallic inclusions that can act as internal notches. Furthermore, impurities tend to segregate in grain boundaries upon solidification and form second-phase particles. The high temperatures attained in the heat-affected zones can alter dispersion distributions or result in less favorable phase relationships in alloy systems exhibiting allotropic transformations.

In addition to these microstructural considerations, contamination during welding and incomplete fusion, resulting in severe notch effects, are possibilities. Thus, there are numerous factors inherent to the welding process that can cause reduced ductilities. Many alloys cannot be welded without severely embrittling the structure. Sufficient care should be taken with the welding of any alloy to insure that its ductility is maintained at the highest possible level. The effect of low temperature is to accentuate these problems.

Although they were not employed in this testing program by the Marshall Space Flight Center, impact and centrally notched fracture toughness specimens are also commonly used to evaluate the susceptibility of a material to brittle fracture.

Materials

In all, 29 alloys were evaluated for their usefulness as low-temperature structural materials by the Marshall Space Flight Center. The alloys and their nominal compositions are listed in table 1. Sheet thicknesses of the various alloys are given in table 2. Some alloys were evaluated with different heat treatments to indicate the optimum structural condition for low-temperature service. The heat treatments applied to each alloy are given in table 3.

Most alloys also were evaluated in the welded condition. Welds were made transverse to the tensile axis using the techniques and filler metals outlined in table 4. Welds in the wrought, sheet alloys were simple, single pass, butt joints. Welds of the cast aluminum alloys were made in 1-inch-thick cast plate using a single, 60-degree V-groove joint design requiring 17 passes.

Testing Procedures

Sheet Specimens

All alloys except the aluminum casting alloys were tested in sheet form. Tests at temperatures ranging from 80 to −320° F and at −450° F were performed using the testing machine illustrated in figure 2. This figure also shows the liquid helium cryostat and associated equipment used for making tensile tests at −450° F. The specimens were located in the cryostat during testing as illustrated in figure 3. An extensometer was used on the

TABLE 1.—*Nominal Chemical Compositions*

Alloy	Element, percent by wt.									
	Al	Cr	Cu	Fe	Mg	Mn	Ni	Si	Ti	Other
Aluminum Alloys										
2014	Balance	------	4.5	------	0.5	1	------	1	------	------
2020	Balance	------	4.5	------	------	0.5	------	----	------	1.1Li, 0.2Ca
2119	Balance	0.005	5.9	0.15	0.003	0.33	0.002	0.06	0.15	------
2219	Balance	0.005	6.0	0.16	0.003	0.33	0.002	0.04	0.06	0.14Zr, 0.12V
5052	Balance	0.25	<0.10	<0.45	2.5	<0.1	------	<0.45	------	------
5086	Balance	<0.25	<0.10	<0.50	4.0	0.45	------	<0.40	------	------
5456	Balance	0.1	<0.20	<0.40	5	0.75	------	<0.40	<0.20	<0.25Zr
7002	Balance	0.15	0.88	0.13	2.07	0.14	------	0.04	0.05	3.35Zn
7075	Balance	0.3	1.6	------	2.5		------	----	------	5.6Zn
7079	Balance	0.15	0.60	<0.40	3.3	0.2	------	<0.30	<0.10	4.5Zn
7178	Balance	0.3	2.0	<0.7	3.0	<0.3	------	<0.50	<0.20	7Zn
195	Balance	------	4.5	<0.8	------	<0.2	------	0.8	<0.2	------
220	Balance	------	----	<0.3	10.0	<0.1	------	0.2	<0.2	------
355	Balance	------	1.3	<0.4	0.5	<0.2	------	5.0	<0.2	------
A356	Balance	------	<0.2	<0.4	0.3	<0.2	------	7.0	<0.2	------
A612	Balance	------	0.5	<0.5	0.7	<0.2	------	0.15	<0.2	6.5Zn
Alloy Steels										
Carpenter 20-Cb	------	20	3.5	Balance	------	<2	25	<1	------	Ta+Cb<1, 2.5Mo
A286	------	16	----	Balance	------	----	26	----	2	------
AISI 202	------	18	----	Balance	------	8	5	<1	------	C<0.15
18 Ni Maraging	0.10	------	----	Balance	------	0.10 max	18	----	0.40	0.03 maxC, 8Co, 5Mo
Titanium Alloys										
Ti-6Al-4V	5.9	------	----	0.12	------	----	------	----	Balance	4V, 0.021C, 0.006H_2, 0.019N_2
Ti-5Al-2.5Sn	5.2	------	----	0.32	------	----	------	----	Balance	2.4Sn, 0.027C, 0.007H_2, 0.019N_2
B120VCA	2.8	11.3	----	0.18	------	----	------	----	Balance	13.4V, 0.027C, 0.005H_2, 0.021N_2.

TABLE 1.—*Nominal Chemical Composition*—Continued

Alloy	Element, percent by wt.									
	Al	Cr	Cu	Fe	Mg	Mn	Ni	Si	Ti	Other
Nickel Alloys										
Inconel X	0.7	15	0.5	7	------	1	Balance	0.5	2.5	1Cb, 1Co
Waspaloy	1.3	19	----	1	------	0.7	Balance	0.4	3	4.3Mo, 14Co+ Trace C, Zr, and B
K-Monel	3	-----	29	1.5	-----	1	Balance	1	0.5	--------------------------
René 41	1.5	20	----	3	------	----	Balance	----	3	10Co, 10Mo
Magnesium Alloys										
LA-91	1	------	----	------	Balance	----	------	----	------	9.0Li
LA-141	1.5	------	----	------	Balance	----	------	----	------	14.5Li

TABLE 2.—*Sheet Thicknesses*

Alloy	Thickness (in.)	Alloy	Thickness (in.)
Aluminum		*Alloy Steels*	
Alloys		Carpenter 20-Cb	0.062
2014	0.062	A286	0.095
2020	0.063	AISI 202	0.066
2119		18 Ni Maraging	0.065
2219	0.090		
5052	0.062	*Titanium Alloys*	
5086	0.062	Ti-6Al-4V	0.062
5456	0.062	Ti-5Al-2.5Sn	0.062
7002	0.25–0.50	B120VCA	0.062
7075	0.25–0.50[a]	*Nickel Alloys*	
7079	0.062	Inconel X	0.063
7178	0.25–0.50[a]	Waspaloy	0.060
195	0.440 dia[b]	K-Monel	0.063
220	0.440 dia	René 41	0.062
355	0.440 dia	*Magnesium*	
A356	0.440 dia	*Alloys*	
A612	0.440 dia	LA-91	0.090
		LA-141	0.090

[a] Machined from 2-inch plate.
[b] Machined from 1-inch cast plate.

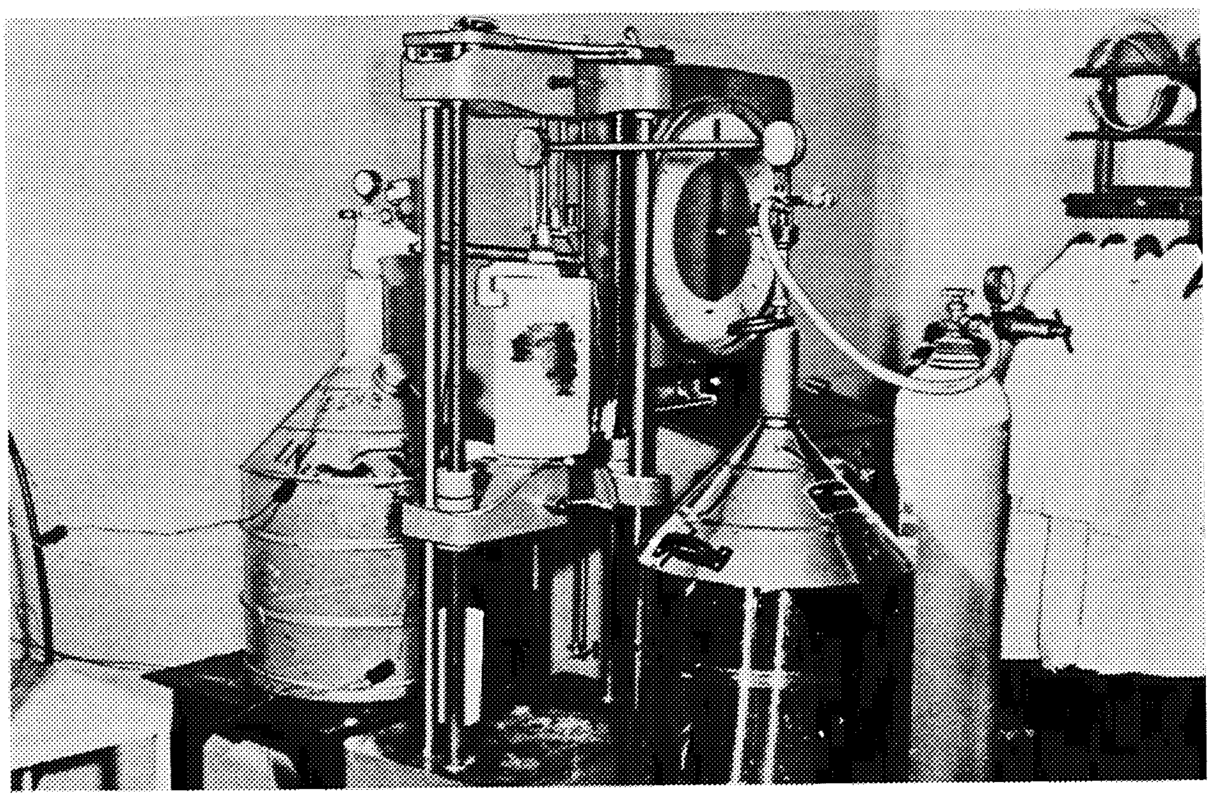

FIGURE 2.—Low-temperature tensile cryostat and accessory equipment.

TABLE 3.—*Heat Treatments*

Alloy	Heat Treatment
Aluminum	
2014	T6—Solution treated and thermally aged [a]
2020	T6—Solution treated and thermally aged [a]
2119	T6—Solution treated and thermally aged [a]
2219	T6—Solution treated and thermally aged [a] or T87—Solution treated, strained, and thermally aged [a]
5052	H3X—Cold worked (20%) [a]
5086	H3X—Cold worked (40%) [a]
5456	H3X—Cold worked (40%) [a]
7002	T6—Solution treated and thermally aged [a]
7075	T6—Solution treated and thermally aged [a]
7079	T6—Solution treated and thermally aged [a]
7178	T6—Solution treated and thermally aged [a]
195	T6—Solution treated and thermally aged [a]
220	T4—Solution treated and aged at room temperature [a]
355	T6—Solution treated and thermally aged [a]
A356	T6—Solution treated and thermally aged [a]
A612	F—Aged at room temperature
Alloy Steels	
Carpenter 20-Cb	Annealed [a]
A286	Annealed and aged 16 hr at 1350° F [b]
AISI 202	Annealed [a]
18 Ni Maraging	Annealed and aged 3 hr at 900° F [b]
Nickel Alloys	
Inconel X	Annealed and aged 20 hr at 1300° F [b]
Waspaloy	Annealed and aged 2 hr at 550° F +16 hr at 1400° F [b]
K-Monel	Annealed and aged 16 hr at 1100° F [b]
René 41	Annealed and aged 16 hr at 1400° F [b]
Titanium Alloys	
Ti-6Al-4V	Annealed [a]
Ti-5Al-2.5Sn	Annealed [a]
B120VCA	Annealed [a]
Magnesium Alloys	
LA-91	
LA-141	

[a] By producer of alloy.
[b] Annealed by producer; aging treatment by MSFC.

TABLE 4.—*Welding Methods*

Alloy	Process	Filler Metal
Aluminum Alloys		
2014	TIG[a]	2319
2020	Not welded	—
2119	Not welded	—
2219	TIG	2319
5052	TIG	5356
5086	TIG	5356
5456	TIG	5556
7002	TIG	MRD 7–5
7075	Not welded	—
7079	Not welded	—
7178	Not welded	—
195	MIG[b]	4043
220	MIG	4043
355	MIG	4043
A356	MIG	4043
A612	MIG	4043
Alloy Steels		
Carpenter 20-Cb	TIG	AISI 347
A286	TIG	A286
AISI 202	TIG	308
18 Ni Maraging	Electron Beam	None
Titanium Alloys		
Ti-6Al-4V	TIG	Ti-6Al-4V
Ti-5Al-2.5Sn	TIG	Ti-5Al-2.5Sn
B120VCA	TIG	B120VCA
Nickel Alloys		
Inconel X	TIG	Inconel X
Waspaloy	TIG	René 41
K-Monel	TIG	K-Monel
René 41	TIG	—
Magnesium Alloys		
LA-91	TIG	EZ33A
LA-141	TIG	EZ33A

[a] Nonconsumable, tungsten electrode inert gas shielded.
[b] Consumable electrode, inert gas shielded.

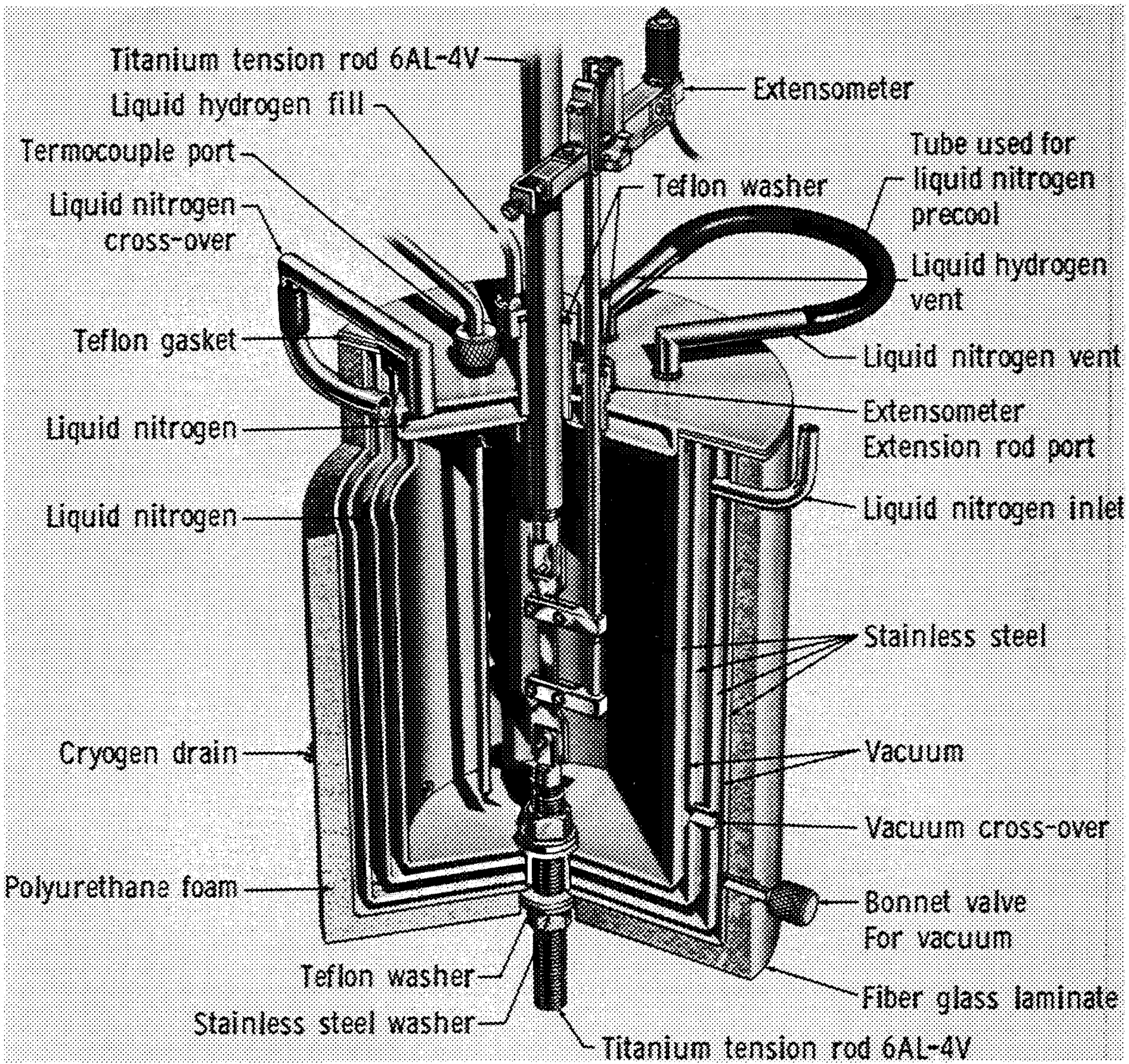

FIGURE 3.—Tensile cryostat showing specimen and extensometer.

unnotched specimens. To obtain temperatures below room temperature and above −320° F, a double-walled aluminum cannister with spray holes around the inner periphery was inserted into the cryostat around the specimen. Liquid nitrogen was sprayed into the space around the specimen to cool it to the desired temperature. The temperature was measured by a copper-constantan thermocouple and controlled by a controller-recorder which actuated a solenoid valve regulating the flow of liquid nitrogen. At −320 and −450° F, the specimens were tested while completely submerged in liquid nitrogen and liquid helium, respectively.

The test temperature of −423° F was obtained by immersing the specimen in liquid hydrogen in a similar cryostat. However, in view of the hazard involved in working with liquid hydrogen, the testing equipment was placed in an open-air location and was remotely controlled as illustrated in figure 4.

Specimen designs are illustrated in figure 5. Notched specimens had the same dimensions as the unnotched specimens with the exception

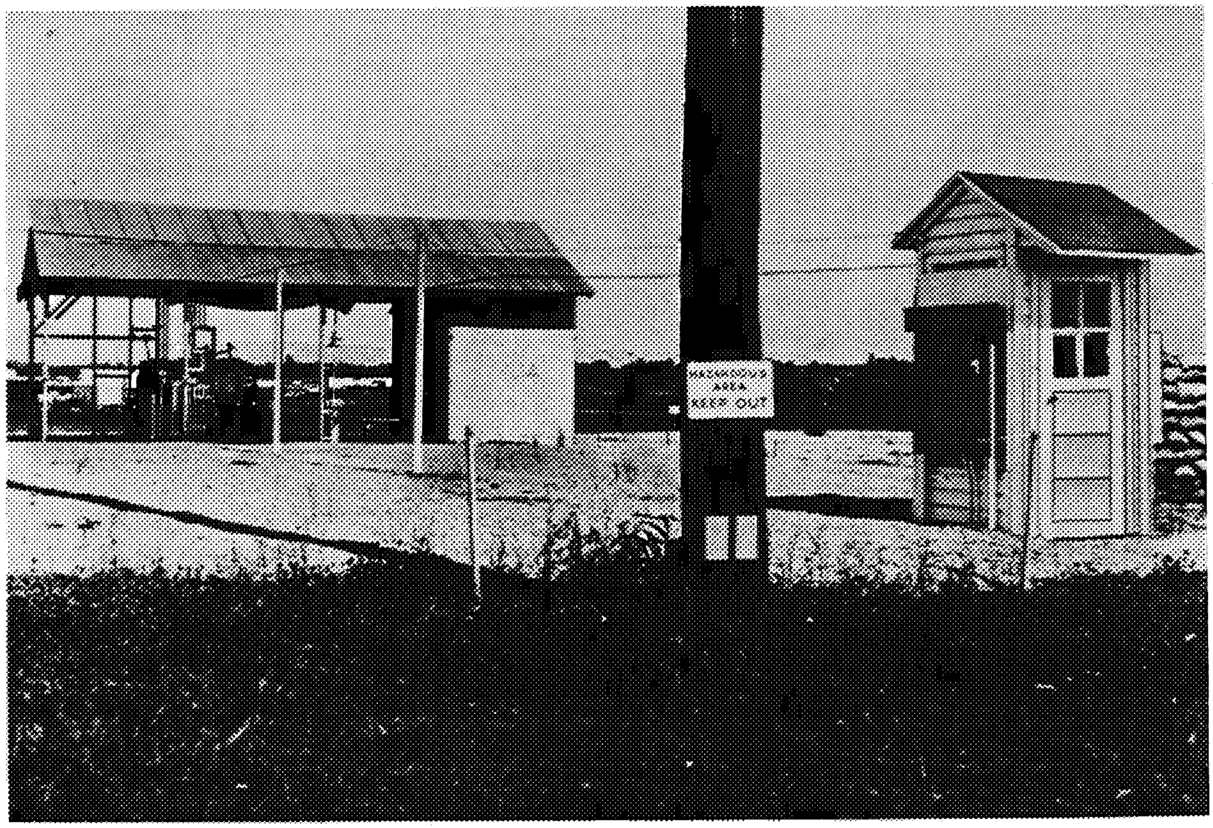

FIGURE 4.—Liquid hydrogen materials research facility.

that a 60-degree notch was cut into the edges of the specimen.

Load-extension curves were autographically recorded for each specimen during testing. All tests were performed at a constant cross-head speed of 0.15 inch/minute. At least three specimens were tested for each alloy and condition at each test temperature. Tabulated average test data for each alloy are reported in appendix A. All wrought materials were tested in the longitudinal direction and some also were tested in the transverse direction. Both sets of data are reported in the appendix. Only the longitudinal tension test data are plotted on the graphs in the following sections.

Bar Specimens

The aluminum casting alloys were evaluated by machining specimens with a 0.440-inch-diameter test section from a 0.500-inch-diameter cast rod, or from a 1-inch-thick cast plate. The gage length was 2.0 inches. Notched tensile data were obtained by testing cast specimens with a machined circumferential 60-degree, 50-percent deep (0.063 in.) notch having a 0.005-inch root radius.

Test temperatures were room temperature and −320° F. Duplicate tests were made for each alloy and test temperature.

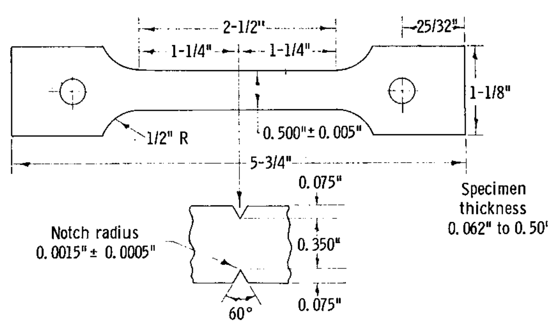

FIGURE 5.—Specimen for notched and unnotched tensile tests of sheet and plate.

Aluminum Alloys

2000 Series

The 2000 series aluminum alloys are essentially aluminum-copper alloys often containing lesser amounts of magnesium, manganese, silicon, or lithium. Copper forms an intermetallic compound with aluminum ($CuAl_2$) and is the primary strengthening ingredient. High strength is achieved by solution annealing at a temperature sufficiently high to dissolve the $CuAl_2$ second phase ($\approx$900–1000° F), followed by aging at a lower temperature ($\approx$200–400° F) to enable coherent precipitate particles to form. Silicon and lithium additions permit the aging reaction to occur at room temperature, although the highest strength is generally still obtained with thermal aging treatment. In addition, silicon improves forgeability and lithium increases the strength. Trace quantities of reactive metals such as manganese and titanium tend to form carbide particles and act as grain refiners. Manganese also improves the resistance to stress corrosion. Iron is a particularly undesirable residual impurity. It forms a complex aluminum-iron-silicon intermetallic compound that tends to locate in grain boundaries, severely lowering the ductility.

Figure 6 illustrates the tensile properties of four 2000 series aluminum alloys in the T6 (thermally aged) condition. The 2020 alloy contains lithium and manganese in addition to copper and is the strongest alloy in the group. However, its ductility is lower than that of the other three alloys, especially at temperatures below approximately −100° F. The notched-unnotched tensile strength ratio indicates that the 2020 alloy is also considerably more susceptible to notch embrittlement.

The strength of the other three alloys decreases in the order 2014, 2219, and 2119. Ductilities are comparable, and are in the vicinity of 10 percent elongation at temperatures down to −450° F. The notched-unnotched strength ratio is less than 1.0 at room temperature and below. However, when this ratio is near 1.0, it indicates that the notch strength was higher than the yield strength, and yielding occurred before fracture. Thus a lack of notch toughness would probably be critical for the 2020 alloy only.

Figure 7 illustrates the effect of variations in treatment on the tensile properties of the 2219 alloy. Straining an age hardenable alloy after solution annealing but prior to aging generally results in the precipitation of finer, more evenly distributed second-phase particles conducive to higher strengths. Thus, the 2219 alloy offers slightly higher strength in the T87 condition (strained 7 percent prior to aging) than in the T6 condition. Ductility is also somewhat higher in the T87 condition, probably due to a minimization of grain boundary precipitation. The lower notched-unnotched strength ratio of material in the T87 condition is largely due to the increased notch severity.

The effect of welding on the tensile properties of 2014 and 2219 alloys in the T6 condition is illustrated in figure 8. Welding significantly decreases the strength of both alloys. This decrease is (probably) attributable to the destruction of the high-strength "aged" structure in the weld metal. The finely distributed second-phase particles in the aged structure coagulate into less effective agglomerate upon overaging in the weld metal.

Welding also reduces the ductility to quite low values. This is usually the result of a high degree of grain-boundary precipitation in the weld metal, in particular the aluminum-iron-silicon intermetallic compound. A general coarsening of the structure of the weld metal also contributes to lower ductilities.

5000 Series

Magnesium is the major alloying constituent in the 5000 series aluminum alloys. Lesser quantities of manganese are generally included. Although an aluminum-magnesium intermetallic compound can be formed, its precipitation during an aging treatment does not increase the strength. A combination of cold work and solid solution strengthening is relied upon to attain improved strengths. In this regard it should be noted that aluminum can contain close to five times more magnesium atoms in solid solution than copper atoms.

Cold working of these alloys is generally followed by a stabilization treatment. This is a high-temperature aging treatment that permits most of the magnesium to remain in solid solution, but improves resistance to stress-corrosion.

Figure 9 illustrates the tensile properties of three 5000 series aluminum alloys in the H3X condition (cold worked* and stabilized). As a group, these alloys are characterized by low strength and high ductility, in comparison with the 2000 series alloys. The strength of the alloys in the 5000 series increases in the order 5052, 5086, and 5456, which is also the order of increasing magnesium and manganese contents, as would be expected in simple solid solution strengthened alloys. A corresponding decrease in ductility accompanies this increase in strength. The elongation of 5052-H32 and 5086-H34 alloys at low temperatures was higher than at room temperature.

The notched-unnotched strength ratio of all of these alloys is slightly less than 1.0 at room temperature, and decreases significantly, at low temperatures. However, because of the excellent ductility at low temperatures and the spread between the yield strengths and tensile strengths, notch embrittlement is probably not a problem for the 5000 series alloys at low temperatures.

Figures 10, 11, and 12 compare the welded and base-metal tensile properties of the 5000 series aluminum alloys. Welding produces a loss in strength but not as much as was observed with the 2000 series alloys. This is no doubt attributable to the different strengthening behaviors of the alloys in the two series. The second-phase distribution in the 2000 series alloys is highly sensitive to thermal exposure. Consequently, its distribution is altered by welding, and there is a significant decrease in strength. However, the distribution of atoms in simple solid solution is not disturbed by thermal exposure. Therefore, by virtue of their reliance on solid solution as a strenghtening mechanism, the strength of the 5000 series alloys is not greatly affected by welding.

The effect of welding on the ductility of the 5000 series alloys is more pronounced than is its effect on strength. Nevertheless, the ductility is not reduced as much as was noted for the 2000 series alloys. Similar to the 2000 series alloys, the reduction in ductility is probably largely due to the formation of second phase particles in grain boundaries of the weld metal during solidification. The presence of impurities, mainly iron, is responsible for the second phase formation.

*10X=percent cold work.

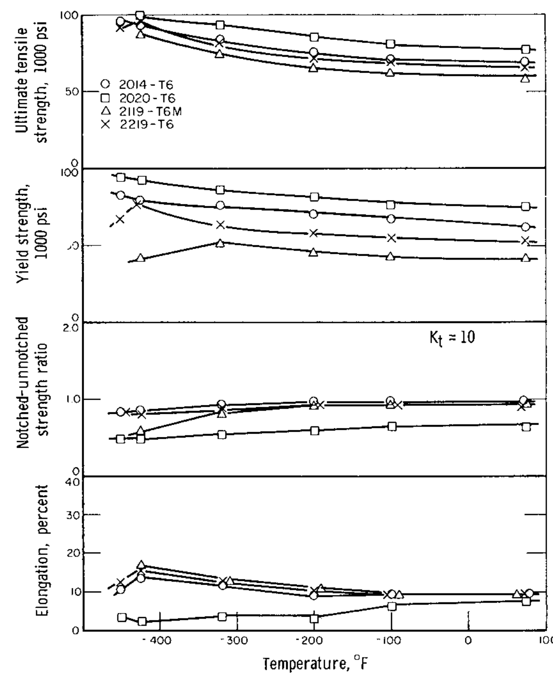

FIGURE 6.—Tensile properties of 2000 series aluminum alloys in the T6 condition.

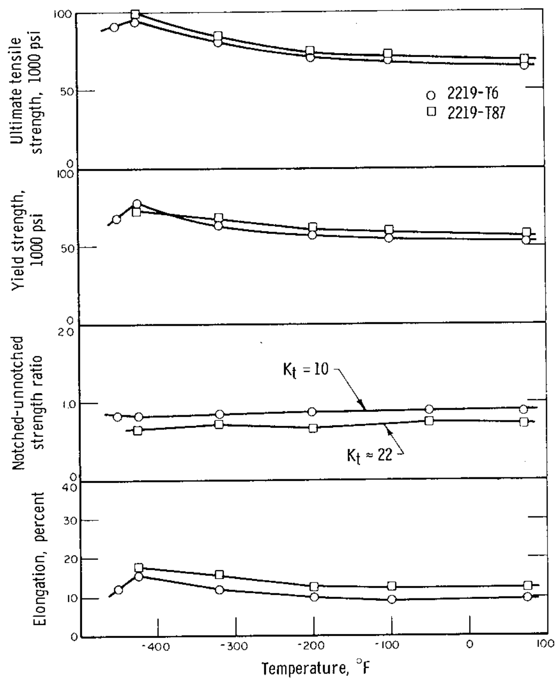

FIGURE 7.—Effect of heat treatment on 2219 aluminum alloy.

7000 Series

The 7000 series aluminum alloys contain magnesium and zinc as major alloying constituents. Lesser amounts of chromium, copper, and manganese are generally included. Like the 2000 series alloys, the 7000 series alloys are dispersion strengthened. High strength results from precipitation of a zinc-magnesium intermetallic compound during a thermal aging treatment. Copper joins in the compound formation and is added as a secondary strengthener. Chromium and manganese improve the resistance to stress-corrosion.

Figure 13 illustrates the tensile properties of four 7000 series aluminum alloys in the T6 condition. The alloys in this group provide higher strengths than alloys in the 5000 series. Strength increases in the order 7002, 7079, 7075, and 7178, which is the order of increasing zinc, and copper plus magnesium content. A corresponding decrease in ductility accompanies the increase in strength. Alloy 7002 offers considerably more ductility than the other three alloys, and, in fact, is more ductile than any of the 2000 series alloys. Thus, 7002 provides a good combination of high strength and superior ductility.

The indicated resistance to notch embrittlement of 7002 is better than that of any of the other aluminum alloys evaluated. Only at −423° F is it weakened by the presence of a notch. Notch embrittlement may be a serious design problem with the other three 7000 series alloys at cryogenic temperatures.

The effect of welding on the tensile properties of 7002 in the T6 condition is illustrated in figure 14. As for the 2000 series alloys, both the strength and ductility are markedly reduced by welding. The explanation of these phenomena presented for the 2000 series alloys also applies to the 7000 series alloys. It is worth noting, however, that the ductility of welded 7002 is somewhat superior to that of the welded 2014 and 2219 series alloys at temperatures down to at least −200° F.

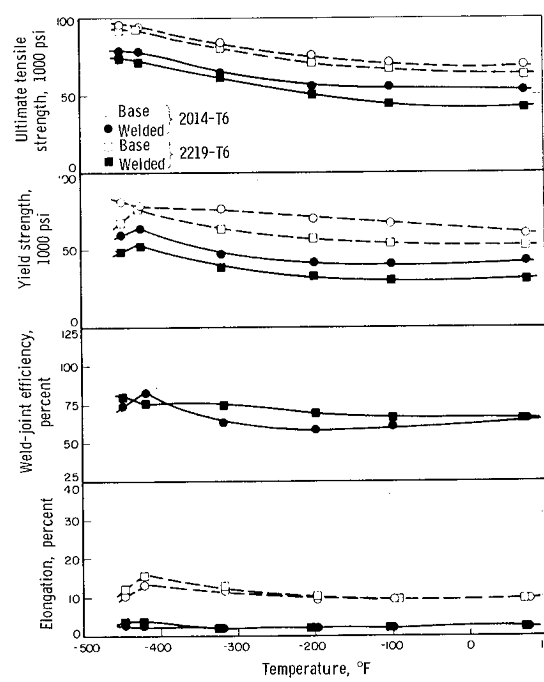

FIGURE 8.—Effect of welding on the tensile properties of 2014 and 2219 aluminum alloys in the T6 condition.

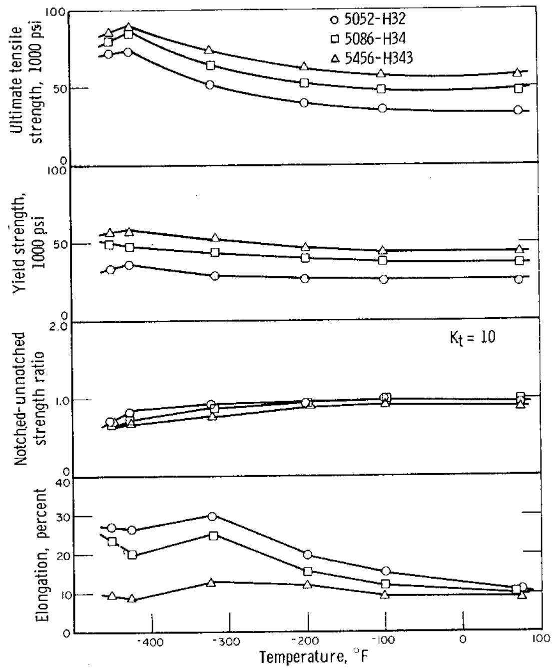

FIGURE 9.—Tensile properties of 5000 series aluminum alloys in the H3X condition.

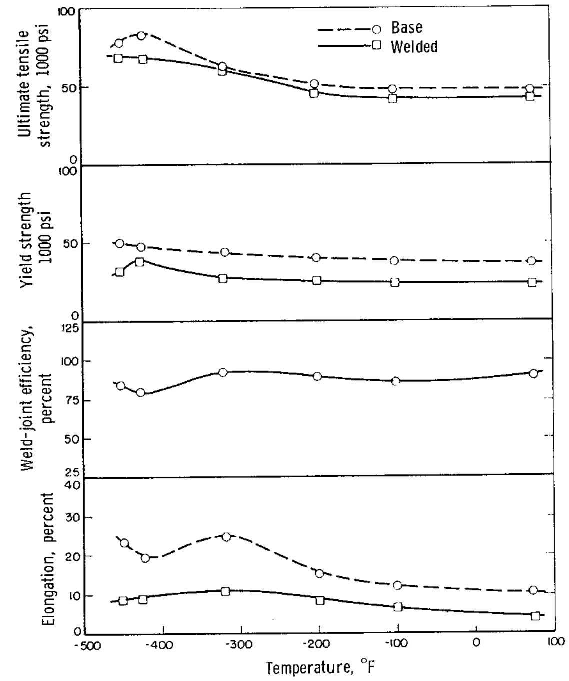

FIGURE 11.—Effect of welding on the tensile properties of 5086 aluminum alloy in the H34 condition.

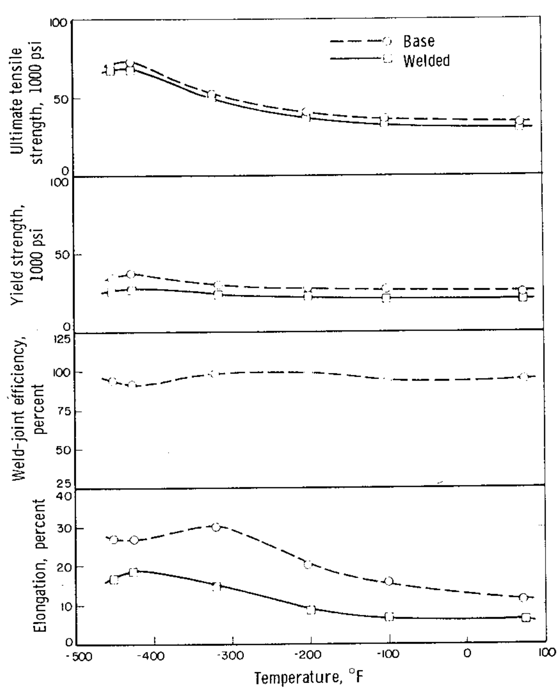

FIGURE 10.—Effect of welding on the tensile properties of 5052 aluminum alloy in the H32 condition.

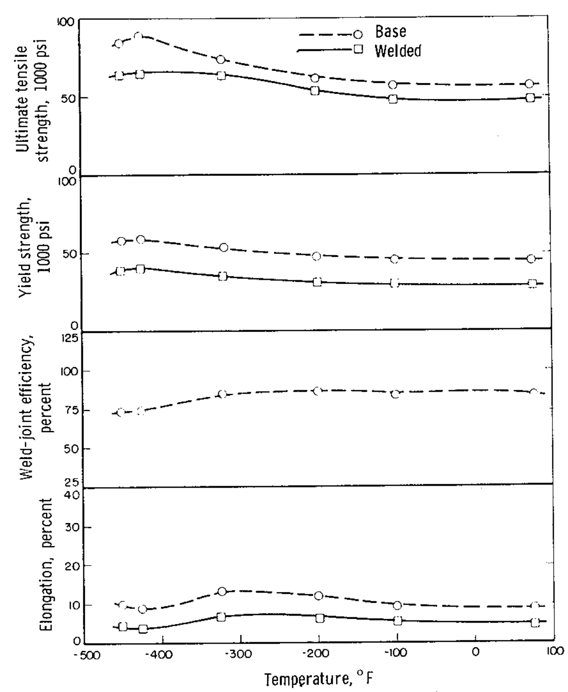

FIGURE 12.—Effect of welding on the tensile properties of 5456 aluminum alloy in the H343 condition.

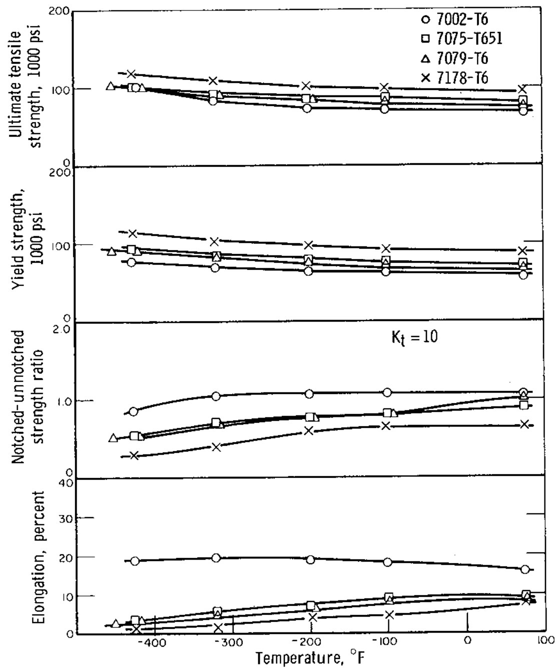

FIGURE 13.—Tensile properties of 7000 series aluminum alloys in the T6 condition.

Casting Alloys

Aluminum casting alloys contain higher amounts of silicon than the wrought alloys to improve the fluidity of the liquid metal. Strengthening is generally achieved by the formation of a complex aluminum-magnesium-silicon intermetallic compound in the matrix during an aging treatment. Copper is also sometimes added as a strengthener.

The tensile properties of five aluminum casting alloys are illustrated in figure 15. The strengths and ductilities of these alloys are considerably lower than those of the 2000 and 7000 series alloys. Although the casting alloys generally exhibit only slightly lower strength than the 5000 series alloys, their ductilities are much lower. Of the casting alloys, 220 offers the highest ductility at room temperature, and A612 the highest at −320° F.

In spite of the low ductilities measured for all of the casting alloys, all of the alloys except 355 exhibited notched-unnotched strength ratios above 1.0 at temperatures down to −320° F.

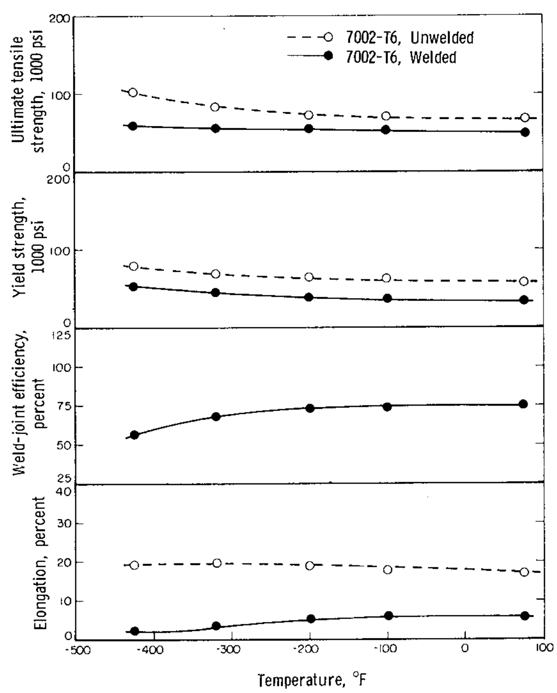

FIGURE 14.—Effect of welding on the tensile properties of 7002 aluminum alloy in the T6 condition.

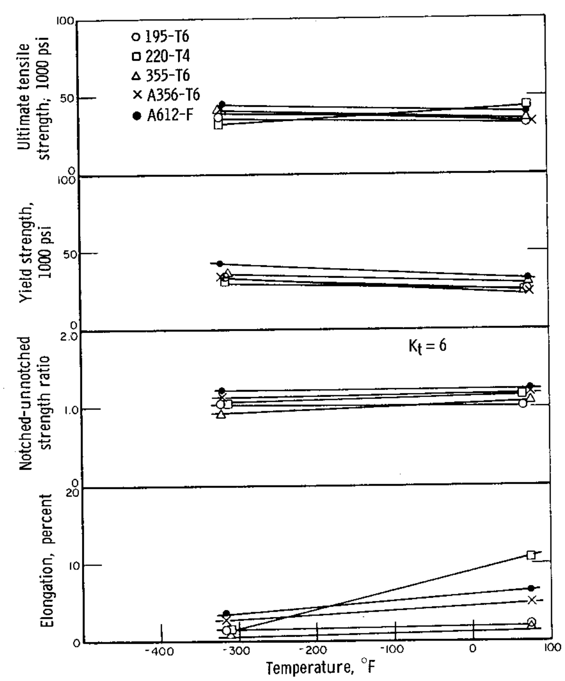

FIGURE 15.—Tensile properties of aluminum casting alloys.

Table 5 shows the effect of welding on the tensile properties of the five casting alloys at room temperature. Strengths are considerably lower for the welded material.

TABLE 5.—*Tensile Properties of Welded Aluminum Casting Alloys at 80° F*

Alloy	Condition	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, percent in 2 in.
195-T6	Welded	29.0	13.8	4.5
	Base	32.7	26.0	2.3
220-T4	Welded	30.0	23.7	2.0
	Base	42.7	26.6	10.8
355-T6	Welded	27.2	15.0	2.5
	Base	31.8	27.1	1.5
A356-T6	Welded	22.4	14.1	2.5
	Base	33.5	24.3	5.0
A612-F	Welded	18.1	15.6	1.1
	Base	38.4	27.0	6.5

Nickel Alloys

Nickel-base alloys have been developed primarily for applications involving corrosion and special physical properties. However, nickel has also been discovered to be an excellent base for the development of alloys for use at elevated and at cryogenic temperatures. Useful strengths can be obtained at temperatures up to 1800–2000° F, as well as at the lowest obtainable cryogenic temperatures.

Chromium and copper display extensive solubility in nickel, and are added to nickel as solid solution strengtheners. In addition, chromium improves the high-temperature oxidation resistance. Most nickel-base alloys, however, rely to a large extent on the precipitation of second-phase particles in the matrix to achieve their high strengths. Aluminum and titanium form intermetallic compounds (Ni_3Al and Ni_3Ti) with nickel and are alloyed with nickel to produce precipitation hardening. The precipitated particles can be dissolved by annealing at high temperatures. Aging at a lower temperature allows them to reprecipitate and strengthen the alloys.

Columbium, cobalt, and molybdenum additions increase the stability of the second-phase particles, and therefore, make them more effective strengtheners at high service temperatures. In addition, molybdenum provides some solid-solution strengthening at high temperatures.

Small quantities of boron and zirconium increase the stress-rupture life of nickel alloys.

Figures 16, 17, 18, and 19 illustrate the tensile properties of Inconel X, K-Monel, Waspaloy, and René 41, respectively. The K-Monel alloy contains copper as the major solid solution strengthener, whereas the other three alloys rely on chromium for this purpose. All of these alloys contain aluminum and titanium for precipitation hardening. Waspaloy and Inconel X provide higher strength than the other two alloys in both the solution-treated and the age-hardened conditions. Aging markedly increases the strength and lowers the ductility of all of the alloys. The ductility decrease associated with age hardening is most pronounced for Waspaloy and René 41. Nevertheless, elongation measurements on the order of 10 percent or more were obtained even at very low temperatures.

The effect of welding on the tensile properties of these nickel alloys in the solution-treated condition is illustrated in figures 20 to 23. No serious loss in mechanical properties attributable to welding is evident for any of the alloys. The welded material displays nearly the same strength as the unwelded material, and ductility is not significantly reduced.

Figures 24 to 27 show that welding after age hardening reduces the strength and decreases the ductility. Similar to the age hardenable aluminum alloys, this decrease in strength is due to the destruction of the high-strength, aged structure in the weld metal. The severe reduction in ductility is probably attributable to the extensive formation of second phase particles in the grain boundaries, or to a eutectic structure in the weld metal, or to a combination of both.

The data for Inconel X and K-Monel indicate that the strength of age-hardened material can be achieved without a serious loss in ductility if the aging treatments are performed after welding solution-treated material. The resulting tensile properties are near those of the age-hardened base material.

In practice, the welding of these nickel alloys in the age-hardened condition should be avoided. The severely reduced ductilities may lead to brittle failure especially if defects are present in or near the weld. If the age-hardened strength is required, aging should be performed after welding. In the case of large welded assemblies that are impractical to age, the designer may have to be content with the solution-annealed strength. Very large weldments are frequently stress-relieved at temperatures and times similar to those necessary for aging. The chief problem is distortion—and the decision depends on material thickness and distribution, and on structural complexity, rather than on the practicability of uniform heating and cooling. There are probably cases where a large weldment must be aged.

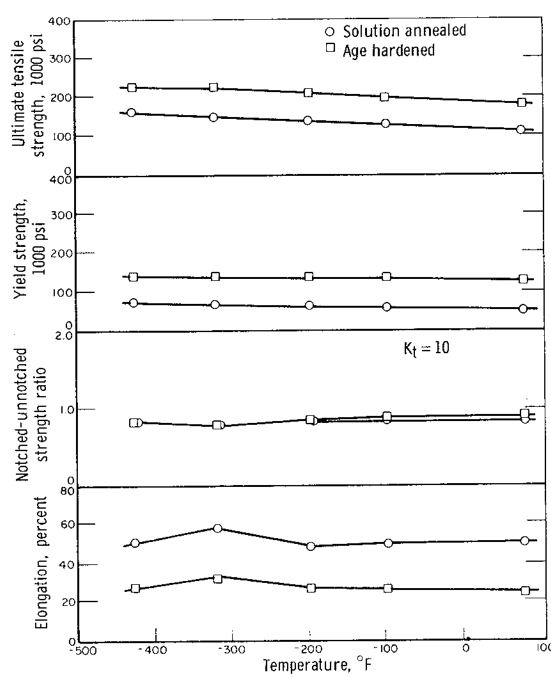

FIGURE 16.—Tensile properties of Inconel X.

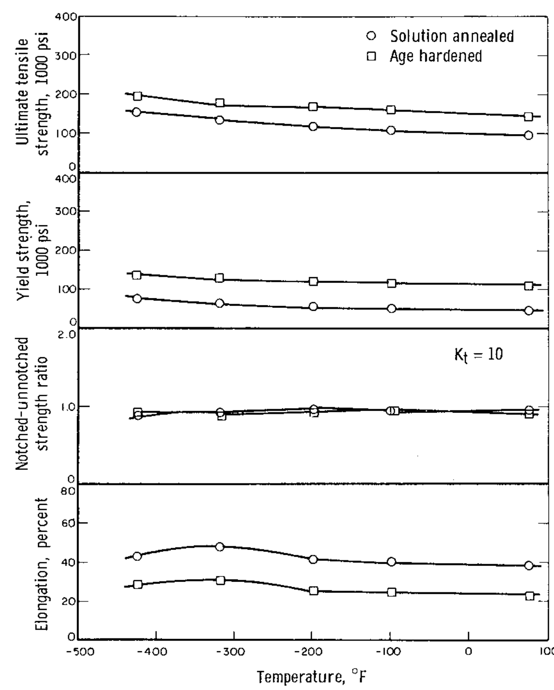

FIGURE 17.—Tensile properties of K-Monel.

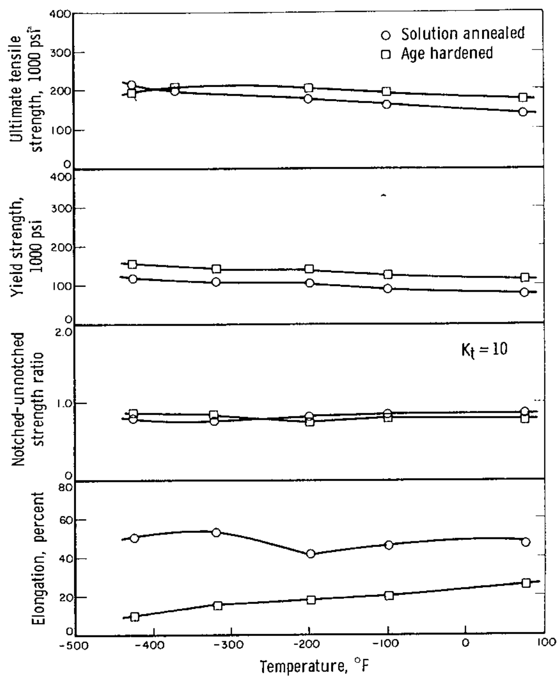

FIGURE 18.—Tensile properties of Waspaloy.

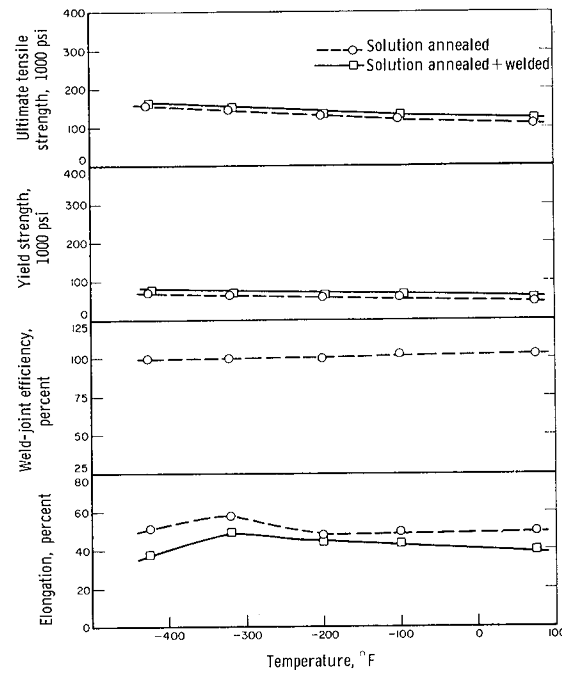

FIGURE 20.—Effect of welding on the tensile properties of solution-annealed Inconel X.

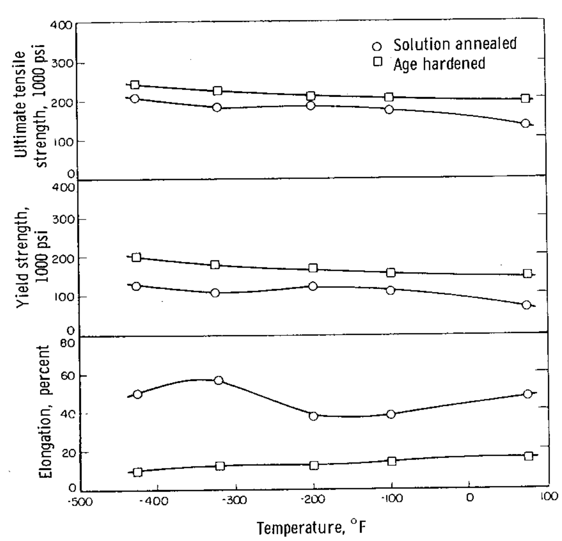

FIGURE 19.—Tensile properties of René 41.

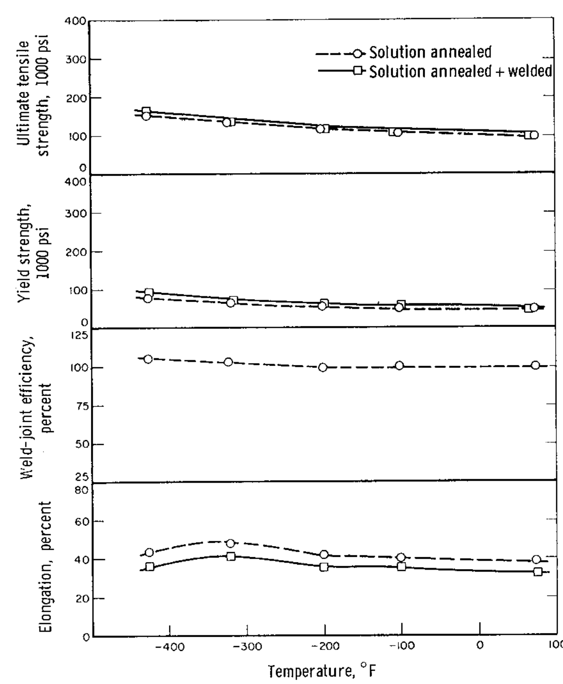

FIGURE 21.—Effect of welding on the tensile properties of solution-annealed K-Monel.

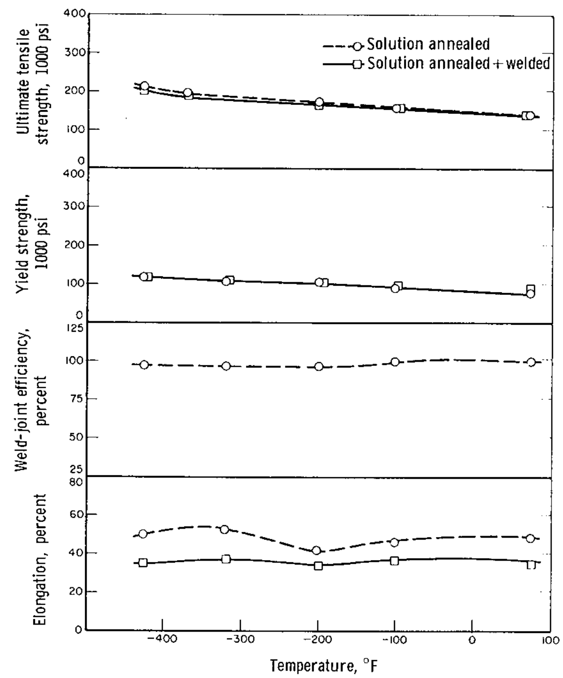

FIGURE 22.—Effect of welding on the tensile properties of solution-annealed Waspaloy.

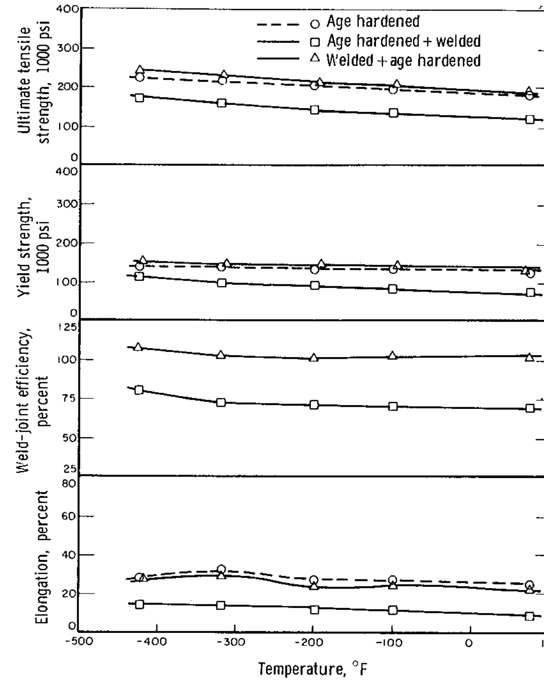

FIGURE 24.—Effect of welding on the tensile properties of age-hardened Inconel X.

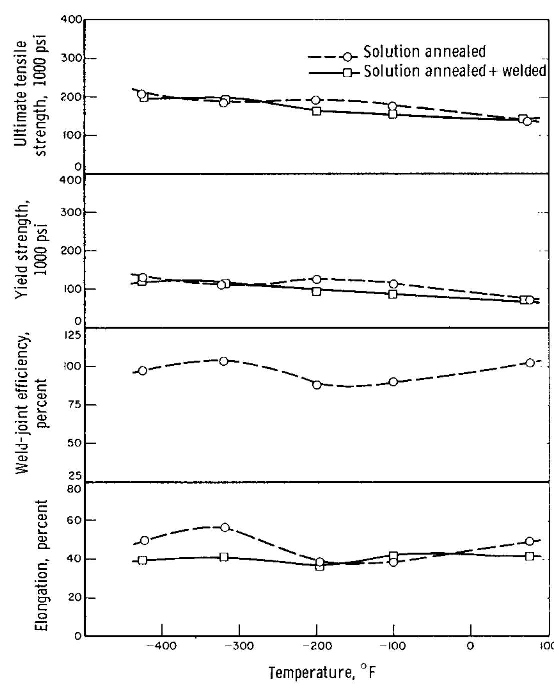

FIGURE 23.—Effect of welding on the tensile properties of solution-annealed René 41.

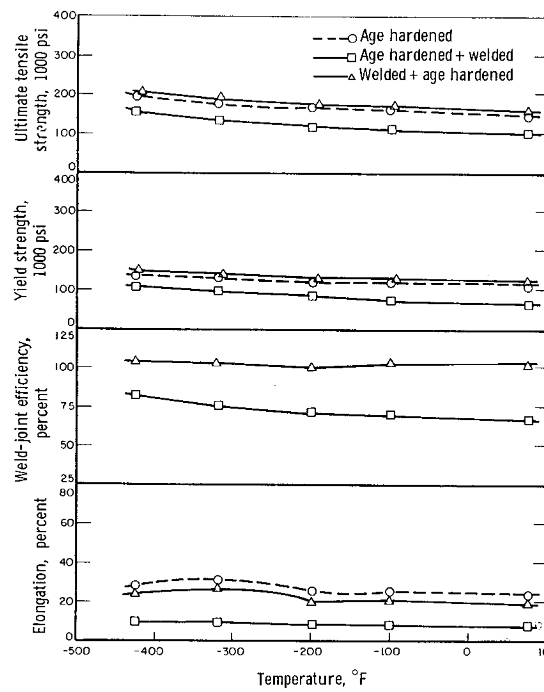

FIGURE 25.—Effect of welding on the tensile properties of age-hardened K-Monel.

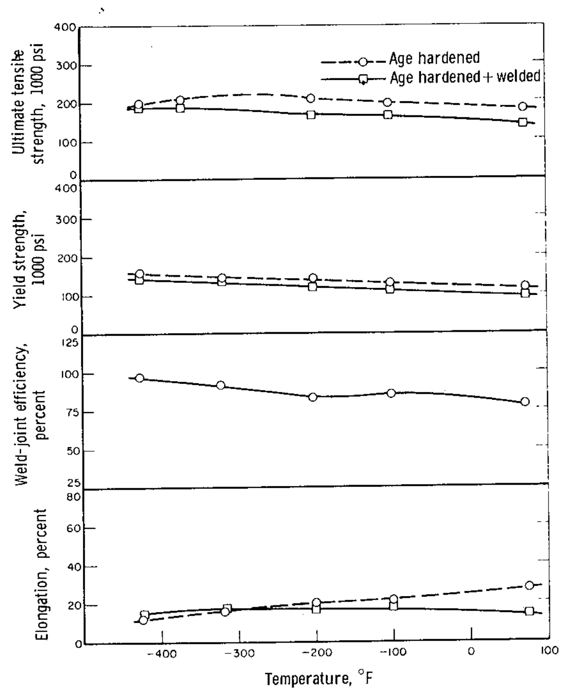

FIGURE 26.—Effect of welding on the tensile properties of age-hardened Waspaloy.

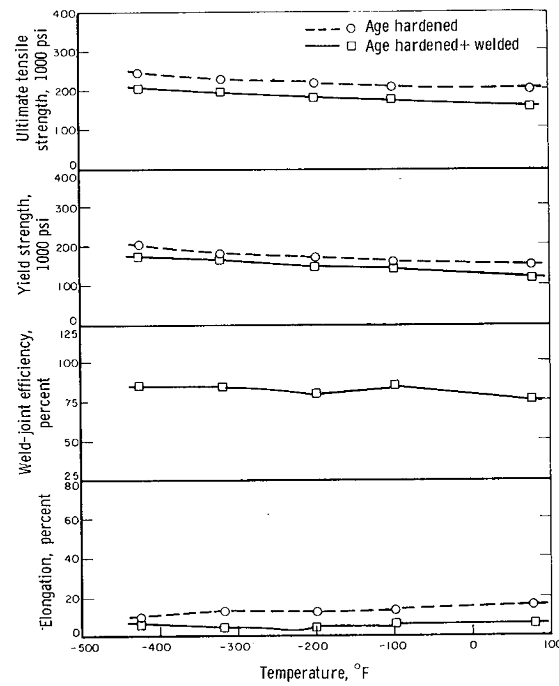

FIGURE 27.—Effect of welding on the tensile properties of age-hardened René 41.

Alloy Steels

Austenitic Stainless Steels

Austenitic stainless steels contain sufficient quantities of such elements as carbon, nickel, nitrogen, and manganese, which stabilize the austenite phase, that they have a single-phase austenitic structure at room temperature. Since austenite has a FCC crystal structure, many of these steels are suited for low-temperature service.

The 300 series austenitic stainless steels contain nickel and chromium as major alloying elements. The two austenitic steels, Carpenter 20-Cb and Type 202, evaluated by the Marshall Space Flight Center are complex modifications of the more common 300 series. Carpenter 20-Cb contains molybdenum, copper, silicon, manganese, tantalum, and columbium in addition to nickel and chromium. Molybdenum, copper, and silicon are added to provide superior corrosion resistance. Tantalum and columbium are added to combine with the carbon and nitrogen to form carbide and nitride second-phase particles in the austenite matrix and, thus, to make the alloy resistant toward intergranular-corrosion attack.

Type 202 stainless steel contains manganese, which is substituted for part of the nickel as an austenite stabilizing element. Originally, this was done to conserve on nickel. It was later found that such a steel has higher strength than its chromium-nickel counterpart.

The tensile properties of these two alloys are illustrated in figure 28. Type 202 offers higher strength at no sacrifice in ductility. The strength of these basically single-phase alloys can be enhanced by cold working. As shown for Type 202 in figure 29, 50 percent cold work increases the strength greatly, at some reduction in ductility. However, the ductility at very low temperatures is still good.

Since the austenitic stainless steels as annealed normally have a single-phase structure,

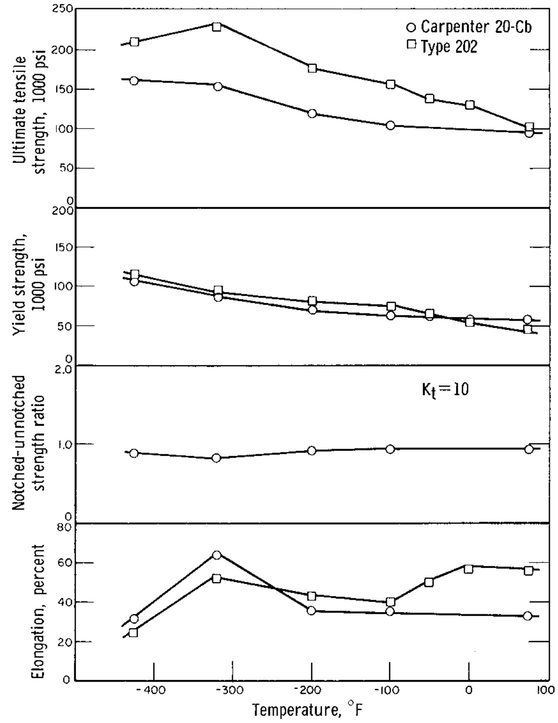

FIGURE 28.—Tensile properties of austenitic stainless steels.

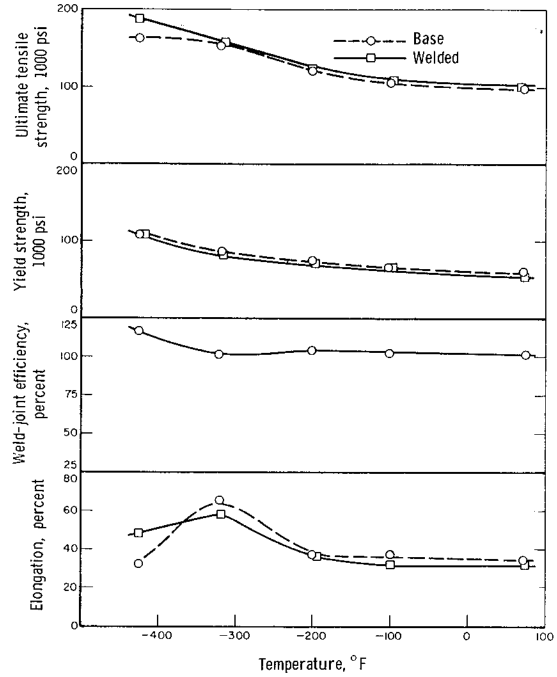

FIGURE 30.—Effect of welding on the tensile properties of Carpenter 20-Cb.

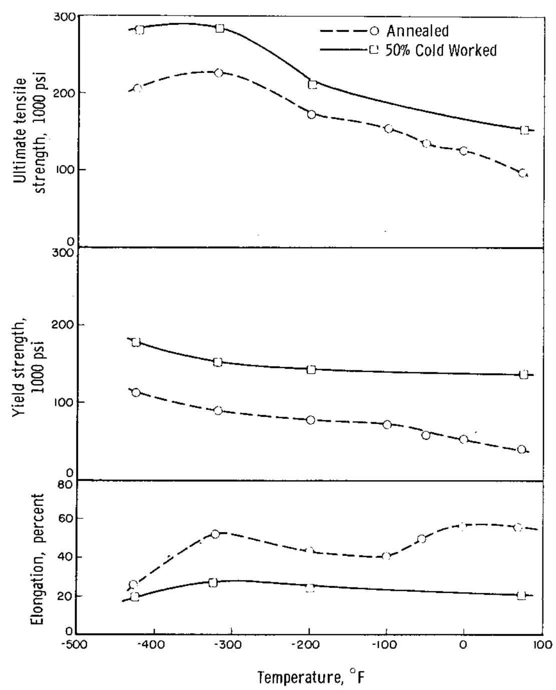

FIGURE 29.—Effect of cold work on the tensile properties of type 202 stainless steel.

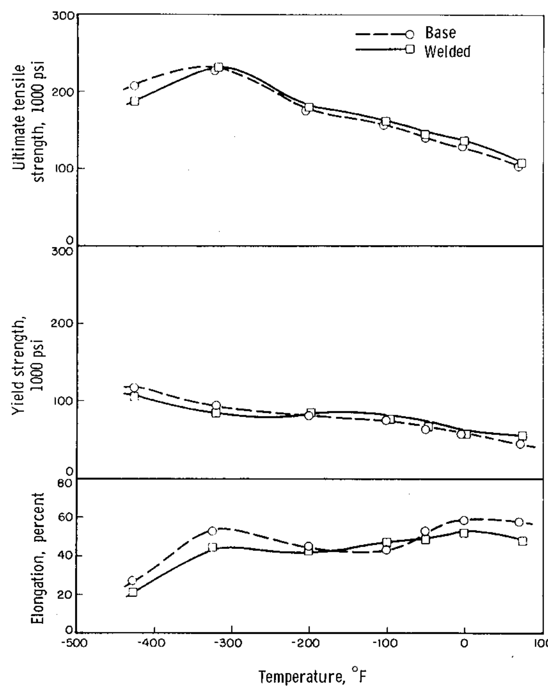

FIGURE 31.—Effect of welding on the tensile properties of annealed type 202 stainless steel.

welding does not severely affect the tensile strength or ductility, as shown in figures 30 and 31. However, the yield strength of cold-worked Type 202 is markedly reduced by welding, as shown in figure 32. The reason for this is the loss of work hardening in the weld metal. The ultimate tensile strength was less affected by welding than was the yield strength because of the ability of the alloy to work harden during the tension test. The ductility was not significantly lowered by welding.

Precipitation-Hardenable Stainless Steels

In the tests reported here, this class of steels is represented by Alloy A286. This alloy contains titanium in addition to nickel and chromium. Titanium forms an intermetallic compound with nickel, and thus enables high strengths to be achieved by the precipitation of nickel-titanium second-phase particles in the austenitic matrix during an aging treatment.

The tensile properties of Alloy A286 are illustrated in figure 33. Aging this alloy significantly increases its strength. Although a decrease in ductility accompanies this increase in strength, the ductility is not reduced to an unacceptable level.

Figures 34 and 35 illustrate the effect of welding on the tensile properties of annealed and of aged A286, respectively. The strength of the annealed material is not significantly altered by welding, and the ductility is not severely lowered. The situation is considerably different for the aged material, however. Welding of age-hardened material reduces the strength and the ductility. Aging after welding restores some, but not all, of the strength and ductility. Thus, unlike the previously discussed nickel alloys, the aged-tensile properties of the parent A286 are not achieved by aging after welding. It is, therefore, best to avoid welding aged material.

18 Percent Nickel Maraging Steels

The 18 percent nickel maraging steels are a relatively new class of steel that is currently undergoing extensive development. The major alloying elements in this steel are nickel, cobalt, molybdenum, and titanium. These steels are martensitic at room temperature.

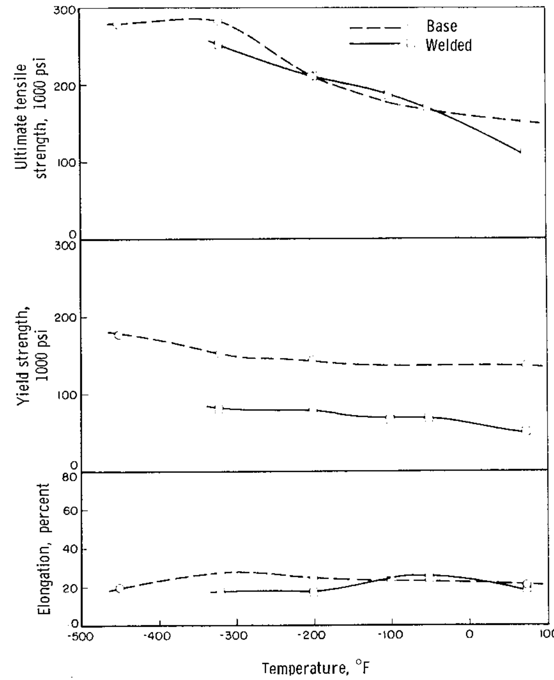

FIGURE 32.—Effect of welding on the tensile properties of 50 percent cold-worked type 202 stainless steel.

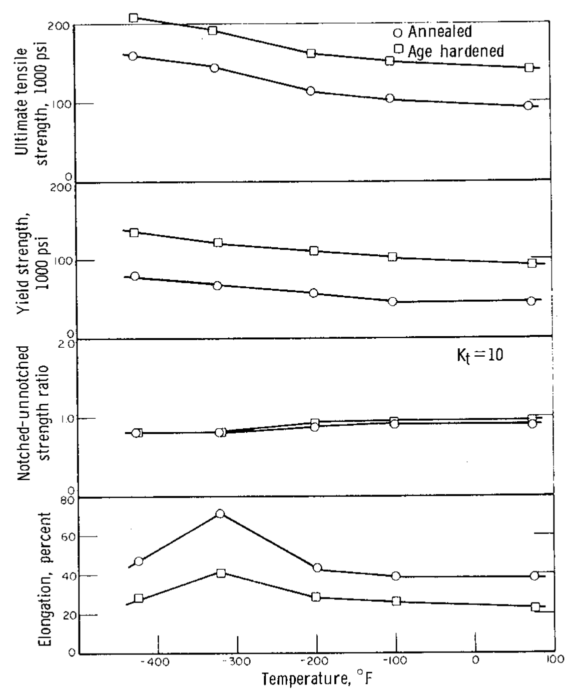

FIGURE 33.—Tensile properties of alloy A286.

However, due to its low carbon content (<0.03 percent C), the martensite is soft and ductile. The steel is annealed by heating to 1500° F followed by air cooling to room temperature. High strengths are then achieved by aging in the vicinity of 900° F, which results in the precipitation of an intermetallic compound in the martensite matrix.

The tensile properties of 18 nickel-8 cobalt-5 molybdenum maraging steel are illustrated in figure 36. Aging markedly increases the strength, but decreases the ductility to less than 10 percent elongation. As the testing temperature was decreased, the strength increased but there was little effect on the ductility. Notch embrittlement is likely to be a serious design problem at temperatures below −320° F.

Figures 37 and 38 show the effect of welding on the tensile properties of annealed and aged maraging steel, respectively. Welding reduces the strength of the annealed material significantly, but does not appreciably alter the strength of aged material. The ductility in both conditions is reduced to a very low level by welding.

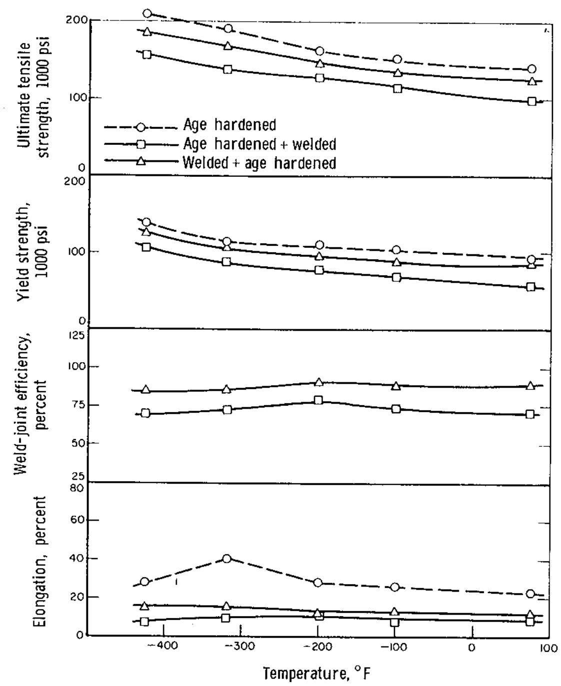

FIGURE 35.—Effect of welding on the tensile properties of age-hardened A286 alloy.

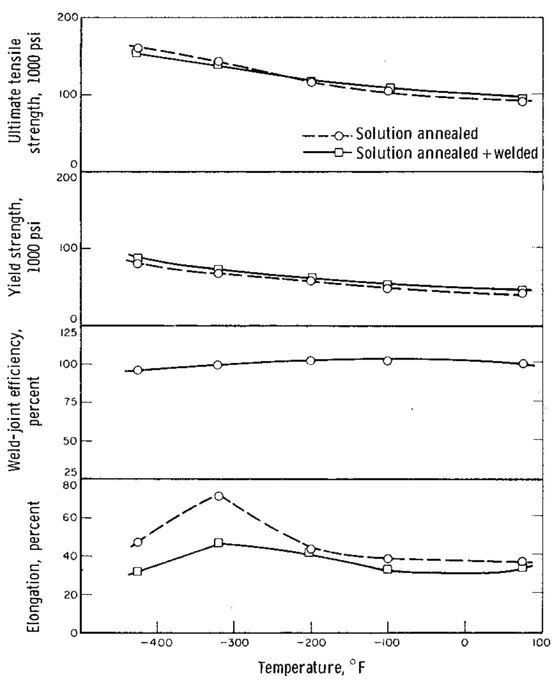

FIGURE 34.—Effect of welding on the tensile properties of solution-annealed A286 alloy.

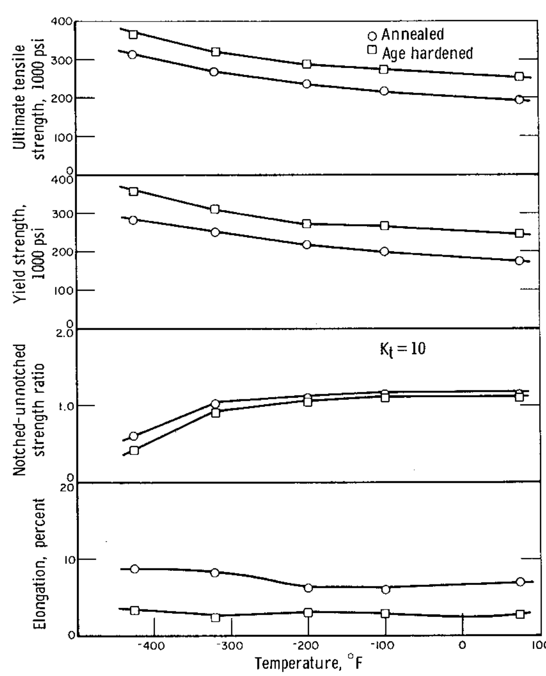

FIGURE 36.—Tensile properties of 18 Ni-8 Co-5 Mo Maraging steel.

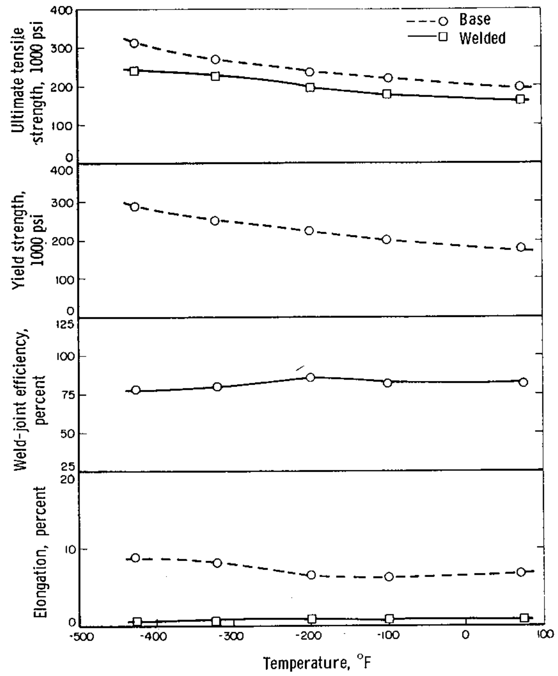

FIGURE 37.—Effect of welding on the tensile properties of annealed 18 Ni-8 Co-5 Mo Maraging steel.

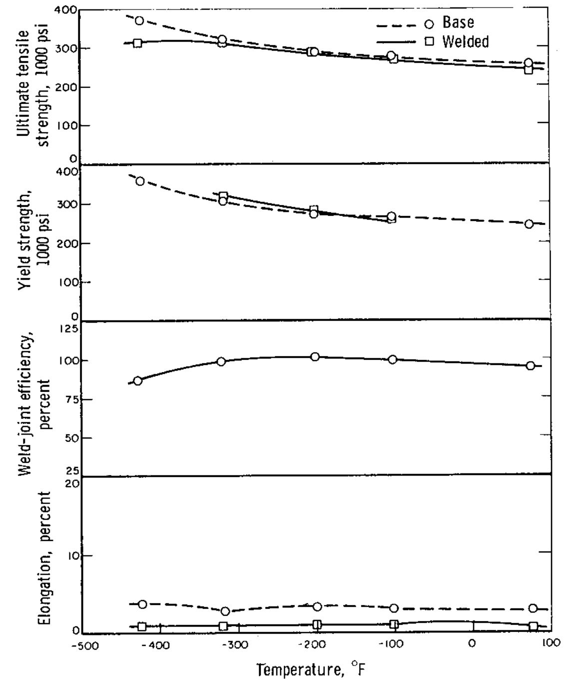

FIGURE 38.—Effect of welding on the tensile properties of age-hardened 18 Ni-8 Co-5 Mo Maraging steel.

Titanium Alloys

Titanium alloys are frequently employed in aircraft gas-turbine compressors and airframes because of their favorable strength/weight ratio, and because they retain useful strength to moderately elevated temperatures. Some titanium alloys also have good mechanical properties at very low temperatures, which makes these alloys suitable for cryogenic applications.

The results of tensile tests conducted on three titanium alloys over the temperature range −453° F to room temperature are given in figure 39. The Ti-13V-11Cr-3Al composition is the strongest, but also displays the least ductility at low temperature. However, it should be noted that the ductilities of the Ti-6Al-4V and Ti-5Al-2.5Sn compositions decrease significantly below −320° F.

All of the titanium alloys studied showed good resistance to notch embrittlement at temperatures down to −200° F. However, the notched-unnotched strength ratios for the Ti-13V-11Cr-3Al alloy are lower than for the other two alloys at temperatures below −200° F. New grades of 5Al-2.5Sn and 6Al-4V alloys are now available with extra low interstitial-element content (ELI) which give much better ductility and notch toughness at −432° F.

For a sound interpretation of the mechanical properties of titanium alloys, an understanding of the influence of the alloying elements on phase relationships is essential. Pure titanium undergoes an allotropic transformation, from the HCP "alpha" phase to the BCC "beta" phase, upon heating through 1615° F. Chromium and vanadium lower this "transus" temperature, and stabilize the beta phase—that is, tend to cause the retention of the beta phase below 1615° F, depending on the amount of chromium and vanadium, and on the rate of cooling. Sufficient quantities of beta-stabilizing chromium and vanadium are present in the

Ti-13V-11Cr-3Al composition to cause a 100 percent beta structure to be present at room temperature.

On the other hand, aluminum and tin stabilize the alpha phase and inhibit the retention of the beta phase. The lower beta-stabilizing alloy content in the Ti-6Al-4V composition produces a mixed alpha-beta structure at room temperature. The absence of a beta-stabilizing element in the Ti-5Al-2.5Sn composition results in a 100 percent alpha structure at room temperature. From the discussion of the ductility transition phenomenon in a previous section of this report, it will be recalled that metals with BCC structures are highly susceptible to embrittlement at low temperatures. Thus, the BCC all-beta Ti-13V-11Cr-3Al alloy has the lowest ductility and least resistance to notch embrittlement at low temperatures. By virtue of its HCP alpha structure, the Ti-5Al-2.5Sn alloy is less susceptible to embrittlement at low temperatures, and therefore exhibits more ductility and resistance to notch embrittlement than the Ti-13V-11Cr-3Al alloy. Due to its mixed alpha-beta structure, the mechanical properties of the Ti-6Al-4V alloy are intermediate between those of the Ti-13V-11Cr and Ti-5Al-2.5Sn alloys.

It must be emphasized that the mechanical properties of titanium alloys are highly sensitive to interstitial element content. Ductility decreases, strength increases and notch sensitivity increases with increasing oxygen, hydrogen, carbon, and nitrogen contents at low-temperatures.

The effect of welding on the tensile properties of Ti-6Al-4V, Ti-5Al-2.5Sn, and Ti-13V-11Cr-3Al alloys is illustrated in figures 40, 41, and 42, respectively. There is no significant effect of welding on the strength of the Ti-6Al-4V and Ti-5Al-2.5Sn alloys, and welding does not seriously reduce their ductility. The slight observed decrease in ductility is probably due to the development of a martensitic "alpha-prime" structure in the weld metal. The alpha-prime structure characteristically has the same strength but lower ductility than the alpha phase.

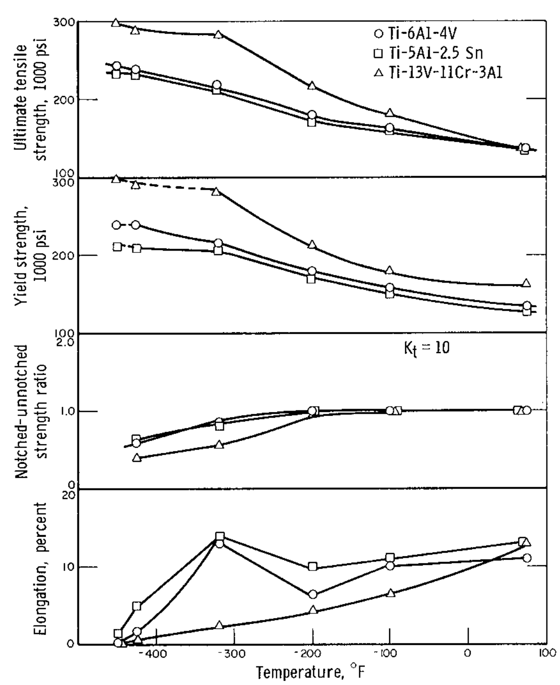

FIGURE 39.—Tensile properties of annealed Titanium alloys.

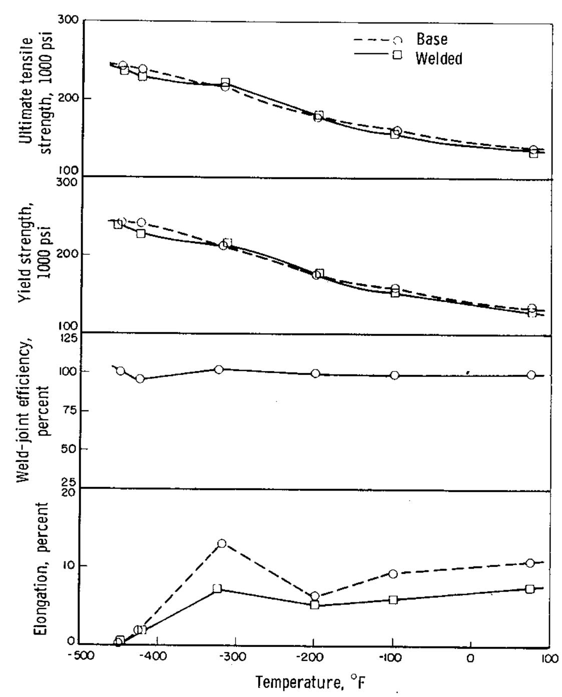

FIGURE 40.—Effect of welding on the tensile properties of Ti-6Al-4V alloy.

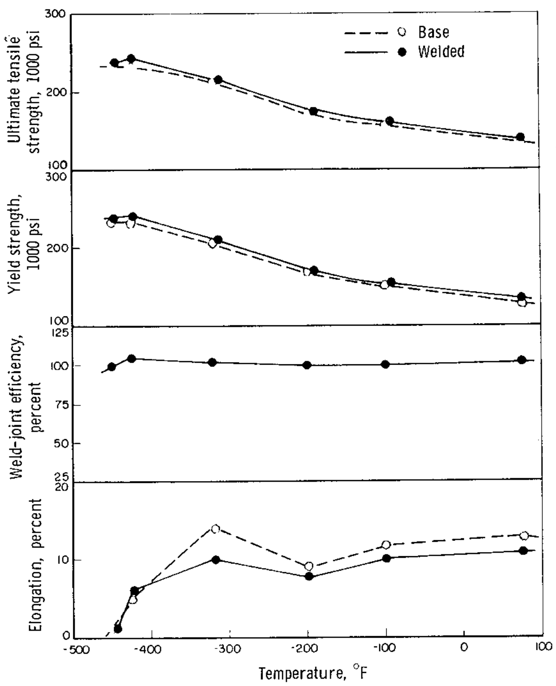

FIGURE 41.—Effect of welding on the tensile properties of Ti-5Al-2.5Sn alloy.

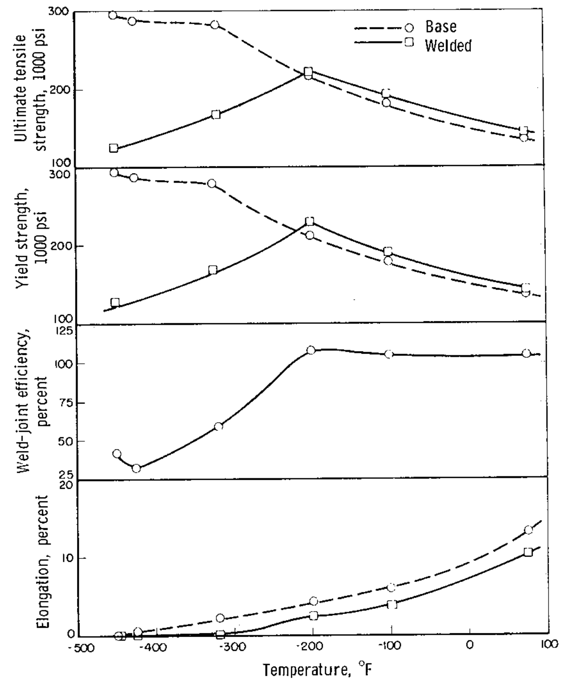

FIGURE 42.—Effect of welding on the tensile properties of Ti-13V-11Cr-3Al alloy.

The Ti-5Al-2.5Sn and Ti-6Al-4V titanium alloys have the highest strength-density ratios of any of the weldable alloys at cryogenic temperatures. For this reason, pressure vessels and other structures that are to be used at −423° F, and that must have minimum weight, are being fabricated of these alloys.

The weld properties are quite different for the Ti-13V-11Cr-3Al composition. Welding had little effect on the strength to −200° F, but below this temperature the strength of the welded specimens was considerably lower than for the parent metal. This may be attributed to interstitial-element pick-up during welding or aging of the weld metal. At temperatures of −300° F and below, the welded joints were extremely brittle, and the strength was considerably lower than that of the base material. The relatively poor weld properties at −300° F and below are probably largely due to the growth of very large grains and grain boundary impurity segregation in the weld metal which is particularly damaging to the ductility of BCC metals.

Magnesium Alloys

Although magnesium is not as strong as other structural metals, it has the lowest density. Magnesium alloys are consequently considered for applications where weight considerations are of prime importance. Alloying with lithium reduces the density and increases the normally low ductility of alpha HCP magnesium. Up to 5.7 percent lithium can be dissolved in alpha magnesium. A beta, BCC phase appears with lithium contents in excess of 5.7 percent. A 100 percent beta structure is obtained when the lithium content exceeds 10.3 percent. Aluminum, zinc, cadmium, and silver can be added to the magnesium-lithium base to strengthen the material by a precipitation hardening mechanism. At present only one alloy, LA-141A, is made in commercial quantities. This alloy contains 14 percent lithium, 1 percent aluminum, balance magnesium.

The tensile properties of LA-91 and LA-141 magnesium alloys are illustrated in figure 43. Both alloys contain 1 to 5 percent aluminum as a primary strengthener and 9 to 14.5 percent lithium to increase ductility and lower density. The 9 percent lithium alpha-beta alloy (LA-91) is slightly stronger than the all beta 14.5 percent lithium alloy (LA-141). Although the LA-141 alloy is less ductile, it offers somewhat better resistance to notch embrittlement. Good ductility is retained in both of these alloys at temperatures down to at least −423° F.

The effects of welding on the tensile properties of LA-91 and LA-141 are illustrated in figures 44 and 45, respectively. Welding tends to lower the strength of both alloys, especially at low temperatures. The ductility of the LA-141 alloy is reduced more by welding than that of the LA-91 alloy. This might be expected due to the all beta (BCC) structure of the LA-141 alloy.

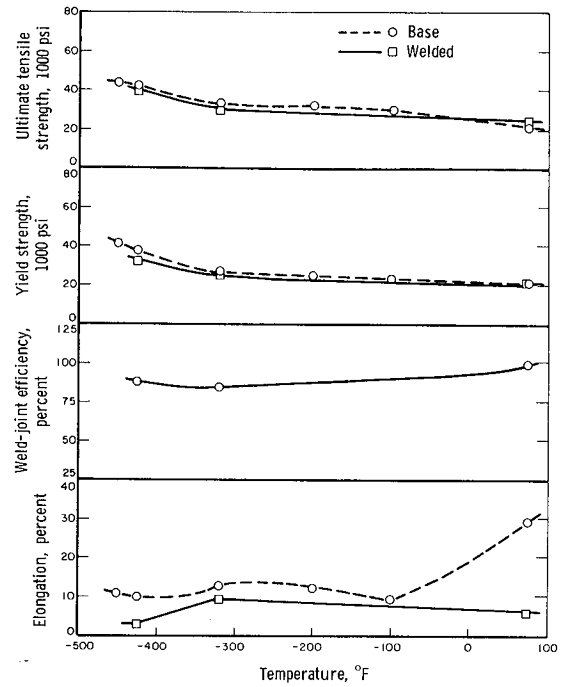

FIGURE 44.—Effect of welding on the tensile properties of LA-91.

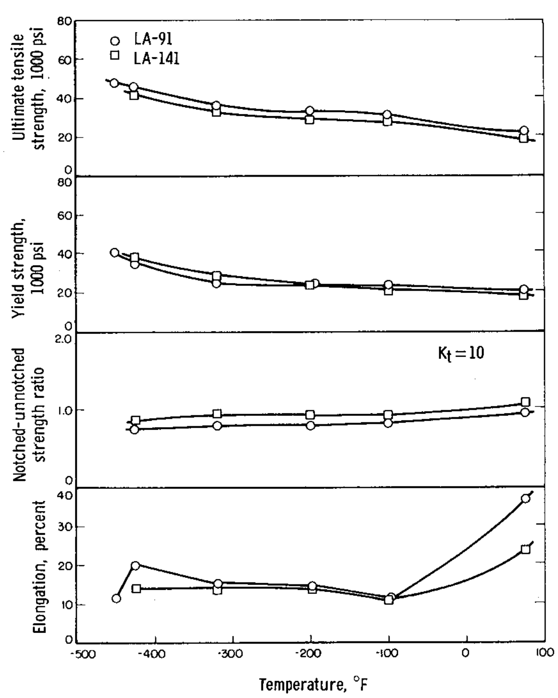

FIGURE 43.—Tensile properties of Mg alloys.

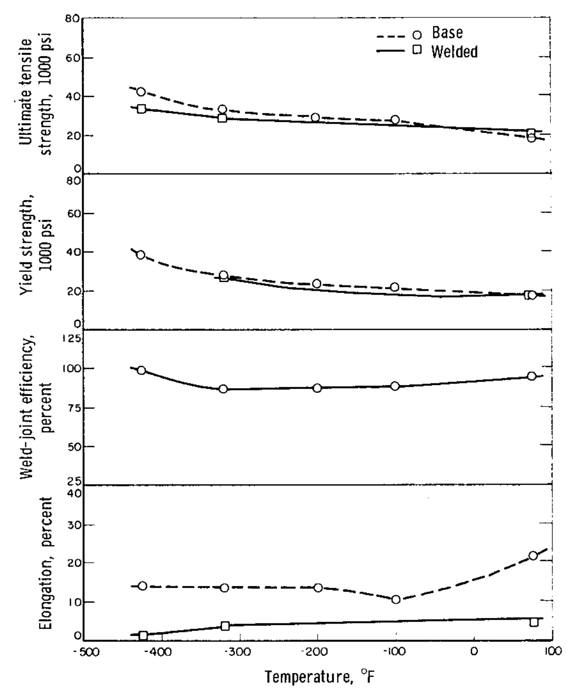

FIGURE 45.—Effect of welding on the tensile properties of LA-141 alloy.

Other Sources of Cryogenic Property Data

This report should not be considered to be a complete survey of metallic materials property data at cryogenic temperatures. Several other publications provide extensive additional information, for example:

(1) "Cryogenic Properties Handbook," Martin Company, Denver, Colorado; Air Force Material Laboratory, Wright-Patterson Air Force Base, Ohio, Contract No. AF 33(657)–9161. Reports are issued quarterly; the Fourteenth Progress Report was issued February 1, 1964, and

(2) Weiss, V., "Aerospace Strucural Metals Handbook," Vols. I and II, Syracuse Univ., AF 33(616)–7792, March, 1963.

Table 6 lists the complementary data, including impact and fracture toughness data that can be found in these two publications for many of the alloys evaluated by the Marshall Space Flight Center. However, the low-temperature properties of several of the alloys have not been previously determined. Of the materials not tested by Marshall, the 300 series austenitic stainless steels deserve special mention as low-temperature structural materials. The titanium alloys 5Al-2.5Sn and 6Al-4V of ELI grade also need to be more thoroughly evaluated at −423° F and −450° F since these alloys have the highest strength-density ratios of any weldable or forgeable alloys at these temperatures. Two new aluminum alloys, 7039 and X7106, are intended to have a good combination of weldability, toughness, and strength at cryogenic temperatures. Further evaluation of these alloys at cryogenic temperatures both as parent metal and as welded specimens would provide important design data.

TABLE 6.—*Additional Low-Temperature Properties on Materials Evaluated by MSFC*

Alloy	Cryogenic Handbook	Aerospace Metals Handbook
2014	✓	✓
2020	✓	✓
2119		
2219	✓	✓
5052	✓	
5086		
5456	✓	
7002		
7075		✓
7079		✓
7178		
195		
220		
355		✓
A356		✓
A612		
Carpenter 20Cb		
A286	✓	✓
202		
18 Ni Maraging		✓
Ti-6Al-4V	✓	✓
Ti-5Al-2.5V	✓	✓
B120VCA	✓	✓
Inconel X	✓	✓
Waspaloy		
K. Monel	✓	
René 41	✓	
LA-91		
LA-141		

Discussion

Many of the 29 alloys evaluated by the Marshall Space Flight Center offer attractive mechanical properties at subzero temperatures. The austenitic stainless steels retain high ductilities at temperatures down to −423° F. The simple, single-phase structure of these alloys enables their excellent low-temperature properties to be maintained after welding. Although they were not evaluated in the Marshall testing program, the 300 series stainless steels in this category should not be overlooked for low-temperature service.

Alpha titanium alloys are appropriate choices for low-temperature service when weight considerations are important. Their combination of low density and relatively high strength enables a lighter structure of equal load-bearing capacity to be built than is possible with austenitic stainless steels. No serious loss in properties results from welding if care is taken not to contaminate the material.

Aluminum alloys have slightly lower densities, but also appreciably lower strength than the titanium alloys. Age-hardened 2000 and 7000 series aluminum alloys provide the highest strengths, but their ductilities (especially of the 7000 series alloys) are marginal at low temperatures. Welding reduces the ductilities to still lower values. The 5000 series aluminum alloys offer considerably higher ductility, which is not appreciably affected by welding, but they are not as strong as the 2000 and 7000 series alloys.

Nickel alloys display high ductilities at very low temperatures in both solution-annealed and age-hardened conditions. It is not advisable to weld material that has been prior age hardened due to severe losses in strength and ductility. The age-hardened properties can generally be attained by aging after welding.

The liquefying and solidifying temperatures of several common substances that often are involved in low-temperature engineering design problems are given in appendix B.

References

1. Parker, E. R., *Brittle Behavior of Engineering Structures*, Wiley, New York, 1957.
2. Cottrell, A. H., *Dislocations and Plastic Flow in Crystals*, Clarendon Press, Oxford, 1953.

Appendix A—Tabulated Test Data

2014–T6

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base					
80	L [a]	70. 0	63. 5	9. 7	0. 99
−100	L	73. 5	68. 0	9. 5	1. 00
−200	L	76. 0	71. 0	9. 3	0. 99
−320	L	84. 0	76. 0	11. 7	0. 93
−423	L	96. 5	79. 5	13. 6	0. 88
−450	L	97. 0	82. 5	10. 4	0. 83
					Joint Efficiency, percent
Welded					
80	L	53. 4	42. 1	2. 0	66
−100	L	56. 1	41. 2	2. 0	60
−200	L	57. 0	42. 4	2. 0	59
−320	L	66. 5	48. 1	2. 0	63
−423	L	78. 2	65. 0	2. 3	82
−450	L	80. 0	61. 2	2. 4	74

[a] Longitudinal to rolling direction.

2020-T6

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base					
80	L[a]	79. 2	75. 1	8. 0	0. 67
	T[b]	80. 2	74. 9	7. 0	
−100	L	81. 8	76. 1	6. 3	0. 65
	T	83. 8	77. 4	5. 0	
−200	L	86. 5	82. 9	3. 0	0. 60
	T	87. 0	79. 3	3. 5	
−320	L	94. 6	87. 9	4. 0	0. 52
	T	93. 2	85. 6	2. 3	
−423	L	101. 4	92. 9	2. 3	0. 50
	T	102. 7	92. 1	3. 0	
−450	L	103. 7	94. 9	3. 6	0. 50
	T	105. 9	93. 9	3. 3	

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

2219-T6

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base					
80	L[a]	65. 4	52. 2	9. 8	0. 92
	T[b]	66. 1	52. 1	10. 3	
−100	L	69. 5	55. 2	9. 3	0. 92
	T	70. 3	54. 6	10. 0	
−200	L	72. 7	58. 3	10. 0	0. 92
	T	72. 9	57. 0	10. 5	
−320	L	82. 3	64. 0	12. 1	0. 90
	T	82. 8	62. 4	12. 5	
−423	L	96. 4	79. 2	15. 3	0. 81
	T	94. 7	77. 8	14. 0	
−450	L	94. 2	69. 1	12. 0	0. 68
	T	95. 9	68. 7	11. 3	

2219-T6—Continued

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Joint Efficiency, percent
			Welded		
80	L	43.0	30.3	2.0	66
−100	L	46.3	30.4	2.0	67
−200	L	50.9	33.9	2.0	70
−320	L	62.0	39.6	2.0	75
−423	L	73.9	52.5	3.3	77
−450	L	75.1	50.6	2.3	80

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

2219-T87

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=22)
			Base		
80	L[a]	68.2	56.3	13.0	0.74
−100	L	72.2	60.3	12.8	0.76
−200	L	74.4	61.9	12.5	0.69
−320	L	84.6	68.2	16.3	0.73
−423	L	100.1	73.0	17.6	0.67

[a] Longitudinal to rolling direction.

2119-T6

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base					
80	L[a]	59. 6	42. 8	9. 0	0. 93
	T[b]	59. 7	42. 6	9. 2	
−100	L	62. 7	43. 7	9. 5	0. 92
	T	62. 9	43. 6	10. 0	
−200	L	66. 3	47. 2	10. 2	0. 90
	T	66. 1	46. 7	9. 3	
−320	L	75. 6	52. 7	12. 2	0. 86
	T	75. 3	51. 2	11. 0	
−423	L	88. 1	42. 9	16. 5	0. 62
	T	87. 1	46. 2	14. 0	

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

5052-H32

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base					
80	L[a]	34. 0	25. 0	10. 6	0. 97
−100	L	36. 0	26. 0	15. 1	1. 01
−200	L	39. 0	27. 0	20. 1	0. 96
−320	L	52. 5	29. 0	30. 0	0. 93
−423	L	73. 0	37. 0	26. 5	0. 88
−450	L	72. 0	33. 0	27. 0	0. 83
					Joint Efficiency, percent
Welded					
80	L	32. 5	20. 5	6. 2	95
−100	L	33. 5	21. 0	6. 9	93
−200	L	38. 5	22. 9	8. 9	98
−320	L	51. 0	24. 2	15. 0	98
−423	L	67. 2	27. 5	19. 0	92
−450	L	68. 2	27. 0	17. 0	95

[a] Longitudinal to rolling direction.

5086-H34

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
			Base		
80	L [a]	47.0	37.0	10.4	1.00
−100	L	48.0	38.0	12.0	0.99
−200	L	52.5	39.0	15.4	0.98
−320	L	64.5	44.0	25.0	0.89
−423	L	85.0	47.5	20.2	0.76
−450	L	80.5	49.0	23.4	0.74
					Joint Efficiency, percent
			Welded		
80	L	42.5	24.6	3.9	90
−100	L	41.5	24.5	6.5	86
−200	L	46.5	26.2	8.2	89
−320	L	60.0	27.5	10.3	93
−423	L	67.5	39.5	9.0	80
−450	L	69.0	32.1	8.6	86

[a] Longitudinal to rolling direction.

5456-H343

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base					
80	L[a]	57. 5	45. 0	8. 7	0. 92
−100	L	57. 0	45. 0	9. 3	0. 90
−200	L	62. 0	47. 0	11. 7	0. 91
−320	L	74. 0	53. 0	13. 0	0. 79
−423	L	87. 0	57. 5	8. 7	0. 75
−450	L	86. 5	57. 0	9. 5	0. 73
					Joint Efficiency, percent
Welded					
80	L	47. 9	28. 7	4. 6	84
−100	L	47. 5	30. 0	5. 3	84
−200	L	53. 4	31. 0	6. 3	86
−320	L	63. 0	34. 8	6. 9	85
−423	L	64. 6	39. 5	3. 5	74
−450	L	64. 2	38. 3	4. 3	74

[a] Longitudinal to rolling direction.

7002-T6

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base					
80	L[a]	66. 9	57. 3	16. 7	1. 05
	T[b]	67. 9	56. 2	16. 0	
−100	L	70. 9	61. 3	18. 0	1. 07
	T	72. 4	60. 7	16. 7	
−200	L	73. 9	64. 1	18. 8	1. 08
	T	75. 4	64. 4	17. 0	
−320	L	83. 4	69. 7	19. 8	1. 03
	T	85. 4	68. 7	19. 0	
−423	L	103. 6	77. 3	18. 9	0. 86
	T	100. 1	73. 0	15. 0	
					Joint Efficiency, percent
Welded					
80	L	49. 4	34. 3	5. 2	74
−100	L	51. 6	36. 4	5. 3	73
−200	L	54. 1	37. 2	5. 0	73
−320	L	56. 8	45. 2	3. 2	68
−423	L	57. 6	50. 8	2. 0	56

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

7075-T651

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base					
80	L[a]	79. 5	73. 8	9. 2	0. 90
	T[b]	83. 4	75. 2	5. 0	
−100	L	83. 5	77. 3	8. 7	0. 82
	T	84. 5	76. 3	3. 0	
−200	L	85. 5	80. 2	6. 7	0. 78
	T	86. 8	80. 7	1. 5	
−320	L	93. 6	87. 9	5. 2	0. 68
	T	97. 9	91. 0	1. 8	
−423	L	101. 0	94. 8	3. 2	0. 56
	T	104. 7	95. 3	1. 5	

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

7079-T6

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base					
80	L[a]	76. 0	67. 0	9. 0	1. 00
−100	L	80. 0	68. 5	9. 0	0. 84
−200	L	86. 5	75. 5	7. 0	0. 78
−320	L	93. 5	84. 0	4. 0	0. 68
−423	L	101. 0	94. 0	3. 0	0. 56
−450	L	102. 0	93. 5	2. 5	0. 53

[a] Longitudinal to rolling direction.

7178-T6

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base					
80	L [a]	93. 8	87. 7	7. 5	0. 67
	T [b]	92. 4	84. 7	8. 7	
−100	L	96. 1	93. 3	4. 0	0. 65
	T	95. 0	88. 1	4. 5	
−200	L	99. 8	96, 0	4. 0	0. 60
	T	97. 9	91. 8	4. 0	
−320	L	109. 0	104. 3	1. 2	0. 41
	T	107. 0	99. 8	1. 5	
−423	L	117. 4	113. 4	1. 0	0. 32
	T	119. 7	106. 3	1. 0	

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

Carpenter 20-Cb

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base					
80	L[a]	95. 5	55. 3	33. 3	0. 92
	T[b]	92. 9	49. 3	36. 3	
−100	L	109. 2	63. 4	36. 2	0. 93
	T	106. 1	58. 6	36. 5	
−200	L	119. 8	71. 2	35. 7	0. 92
	T	115. 5	67. 0	39. 8	
−320	L	153. 8	86. 7	64. 0	0. 82
	T	149. 5	80. 3	64. 3	
−423	L	162. 8	104. 5	30. 1	0. 89
	T	179. 7	99. 4	53. 8	
					Joint Efficiency, percent
Welded					
80	L	96. 8	52. 7	31. 7	101
−100	L	111. 4	63. 7	32. 7	102
−200	L	124. 4	70. 7	37. 7	105
−320	L	155. 3	84. 7	58. 0	101
−423	L	190. 7	108. 5	49. 0	117

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

A286

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base—Solution Annealed					
80	L[a]	92. 6	42. 0	37. 3	0. 86
	T[b]	92. 8	44. 0	42. 0	
−100	L	104. 2	48. 1	38. 8	0. 88
	T	104. 6	51. 7	44. 5	
−200	L	115. 3	56. 6	43. 0	0. 87
	T	113. 2	58. 1	46. 5	
−320	L	144. 1	68. 3	71. 0	0. 80
	T	145. 7	70. 8	75. 7	
−423	L	160. 9	80. 8	47. 3	0. 82
	T	143. 8	85. 4	39. 9	

A286—Continued

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Joint Efficiency, percent
Base—Age Hardened					
80	L	140. 5	93. 6	22. 0	0. 94
	T	149. 7	109. 2	24. 8	
−100	L	152. 9	101. 0	25. 7	0. 92
	T	162. 7	113. 6	27. 3	
−200	L	161. 9	110. 3	28. 2	0. 90
	T	171. 9	121. 7	27. 3	
−320	L	191. 2	122. 3	40. 7	0. 82
	T	197. 2	129. 9	41. 8	
−423	L	218. 4	137. 0	28. 5	0. 83
	T	220. 5	142. 6	36. 5	
Welded—Annealed					
80	L	93. 0	43. 7	34. 0	100
−100	L	105. 5	51. 4	33. 0	101
−200	L	116. 2	59. 8	42. 2	101
−320	L	142. 4	73. 6	47. 0	99
−423	L	154. 9	88. 9	32. 0	96
Welded—Pre-Aged					
80	L	99. 3	56. 0	8. 8	71
−100	L	113. 2	68. 4	8. 0	74
−200	L	127. 3	78. 8	11. 0	79
−320	L	137. 5	87. 2	9. 0	72
−423	L	155. 1	104. 0	7. 8	71
Welded—Post-Aged					
80	L	124. 9	87. 2	11. 0	89
−100	L	135. 0	88. 4	13. 2	88
−200	L	146. 0	97. 0	12. 8	90
−320	L	166. 1	107. 9	15. 8	87
−423	L	186. 5	125. 6	15. 3	85

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

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Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Joint Efficiency, percent
		Base—Annealed			
80	L[a]	101.5	47.1	56.8	
0	L	129.2	55.7	57.3	
−50	L	139.8	61.0	50.7	
−100	L	156.0	70.2	40.7	
−200	L	176.0	78.3	43.7	
−320	L	231.2	88.3	51.7	
−450	L	206.4	111.0	25.0	
		Base—50% Cold Worked			
80	L	156.2	139.9	21.0	
−200	L	214.7	147.6	25.2	
−320	L	286.2	154.6	28.2	
−450	L	283.35	180.35	20.3	
		Welded—Annealed			
80	L	107.5	55.6	48.3	106
0	L	129.3	56.6	52.6	100
−50	L	143.3	63.7	49.8	103
−100	L	158.5	73.5	46.8	101
−200	L	177.0	78.9	43.0	100
−320	L	230.1	83.4	45.0	100
−450	L	188.9	105.7	21.5	91
		Welded—50% Cold Worked			
80	L	112.5	53.6	19.6	72
−50	L	176.3	70.1	25.0	------
−100	L	188.0	68.1	24.2	------
−200	L	219.9	78.2	18.5	------
−320	L	255.4	82.6	18.7	90

[a] Longitudinal to rolling direction.

Maraging Steel

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
			Base—Annealed		
80	L[a]	192. 3	175. 0	7. 0	1. 16
	T[b]	191. 8	172. 8	6. 2	1. 17
−100	L	217. 6	199. 2	6. 0	1. 14
	T	215. 0	195. 0	5. 8	1. 15
−200	L	234. 3	216. 4	6. 3	1. 13
	T	233. 3	214. 3	5. 7	1. 13
−320	L	268. 0	250. 3	8. 0	1. 01
	T	270. 4	251. 4	7. 5	1. 03
−423	L	313. 0	282. 7	8. 7	. 59
	T	307. 3	269. 6	7. 2	. 53
			Base—Aged		
80	L	253. 7	245. 3	2. 8	1. 09
	T	250. 8	238. 9	4. 0	1. 12
−100	L	275. 3	266. 0	2. 8	1. 08
	T	277. 9	270. 2	3. 2	1. 07
−200	L	287. 7	274. 3	3. 0	1. 06
	T	292. 1	279. 3	2. 8	1. 05
−320	L	321. 3	309. 1	2. 5	. 90
	T	329. 5	314. 7	3. 0	. 88
−423	L	365. 0	355. 1	3. 2	. 41
	T	382. 3	369. 4	2. 0	. 38
					Joint Efficiency, percent
			Welded—Annealed		
80	L	156. 9		0. 5	82
−100	L	177. 0		0. 5	82
−200	L	198. 8		0. 6	85
−320	L	222. 6		0. 3	79
−423	L	244. 4		0. 3	78
			Welded—Aged		
80	L	237. 5		0. 5	94
−100	L	276. 2	273. 2	0. 6	100
−200	L	292. 2	284. 9	1. 0	102
−320	L	318. 5	314. 0	0. 5	99
−423	L	313. 5		0. 5	86

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

Inconel X

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base—Annealed					
80	L[a]	110. 7	48. 3	50. 7	0. 82
	T[b]	113. 5	49. 5	51. 0	
−100	L	122. 2	52. 9	50. 5	0. 82
	T	123. 1	54. 3	50. 7	
−200	L	131. 3	58. 4	48. 5	0. 83
	T	132. 5	59. 4	49. 7	
−320	L	149. 7	65. 4	58. 3	0. 79
	T	150. 1	66. 3	57. 7	
−423	L	160. 1	70. 4	51. 3	0. 82
	T	167. 4	71. 4	58. 7	
Base—Age Hardened					
80	L	179. 7	125. 5	25. 3	0. 90
	T	180. 6	126. 7	25. 5	
−100	L	194. 0	132. 4	26. 7	0. 87
	T	193. 9	134. 5	26. 0	
−200	L	203. 2	135. 7	27. 2	0. 84
	T	203. 5	138. 3	26. 5	
−320	L	220. 4	139. 4	32. 0	0. 79
	T	219. 9	142. 6	34. 0	
−423	L	223. 8	140. 0	28. 0	0. 82
	T	236. 8	144. 0	32. 8	
					Joint Efficiency, percent
Welded—Annealed					
80	L	113. 0	54. 0	40. 8	102
−100	L	124. 4	58. 7	44. 2	102
−200	L	131. 7	63. 0	44. 7	100
−320	L	149. 8	69. 3	49. 7	100
−423	L	160. 6	74. 0	38. 0	100

Inconel X—Continued

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Joint Efficiency, percent
Welded—Pre-Aged					
80	L	119. 7	72. 3	8. 5	67
−100	L	134. 6	85. 9	10. 2	69
−200	L	143. 4	93. 5	10. 7	71
−320	L	157. 7	98. 3	14. 0	72
−423	L	176. 9	115. 1	14. 5	79
Welded—Post-Aged					
80	L	181. 1	125. 4	22. 5	101
−100	L	195. 4	132. 8	24. 3	101
−200	L	204. 2	136. 4	23. 5	100
−320	L	223. 7	137. 3	29. 7	102
−423	L	240. 9	147. 5	28. 0	108

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

Waspaloy

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base—Annealed					
80	L [a]	143. 9	79. 9	48. 0	0. 85
	T [b]	141. 9	77. 0	48. 7	
−100	L	159. 2	93. 6	45. 5	0. 85
	T	162. 4	93. 9	44. 0	
−200	L	172. 8	104. 9	42. 0	0. 83
	T	171. 4	94. 8	44. 0	
−320	L	199. 9	108. 1	53. 0	0. 77
	T	194. 9	115. 2	47. 7	
−423	L	213. 7	118. 4	50. 4	0. 80
	T	217. 4	116. 7	49. 3	

See footnotes at end of table.

Waspaloy—Continued

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base—Age Hardened					
80	L	177. 6	115. 9	26. 3	0. 81
	T	180. 3	115. 9	19. 8	
−100	L	193. 4	128. 1	20. 5	0. 81
	T	195. 9	128. 0	22. 3	
−200	L	203. 5	138. 7	18. 8	0. 79
	T	200. 5	131. 6	18. 0	
−320	L	204. 6	142. 2	15. 0	0. 80
	T	211. 3	145. 3	14. 0	
−423	L	196. 7	153. 9	10. 2	0. 85
	T	207. 5	155. 4	11. 3	
					Joint Efficiency, percent
Welded—Annealed					
80	L	143. 4	88. 2	34. 8	100
−100	L	159. 9	96. 6	36. 7	100
−200	L	168. 3	101. 3	34. 2	97
−320	L	191. 7	111. 8	37. 2	96
−423	L	206. 9	115. 9	35. 0	97
Welded—Pre-Aged					
80	L	140. 5	99. 7	7. 2	79
−100	L	166. 0	113. 5	9. 2	86
−200	L	169. 3	121. 9	8. 5	83
−320	L	188. 7	140. 0	8. 7	92
−423	L	192. 0	143. 0	7. 5	97

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

K-Monel

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base—Annealed					
80	L [a]	95. 1	45. 6	38. 8	0. 95
	T [b]	95. 2	45. 8	36. 5	
−100	L	105. 6	50. 6	40. 0	0. 95
	T	106. 9	52. 2	40. 5	
−200	L	114. 5	56. 6	41. 0	0. 96
	T	144. 0	57. 3	40. 5	
−320	L	133. 4	65. 0	48. 0	0. 91
	T	132. 5	63. 6	44. 7	
−423	L	152. 0	74. 7	43. 3	0. 86
	T	153. 0	83. 2	42. 5	
Base—Age Hardened					
80	L	148. 0	105. 9	22. 7	0. 92
	T	147. 5	104. 3	22. 3	
−100	L	156. 2	111. 2	24. 0	0. 96
	T	159. 2	113. 5	23. 5	
−200	L	164. 8	119. 0	24. 7	0. 93
	T	165. 9	120. 0	24. 7	
−320	L	176. 7	128. 1	30. 7	0. 92
	T	182. 6	132. 3	30. 5	
−423	L	192. 0	136. 9	28. 3	0. 90
	T	196. 9	135. 8	29. 2	
					Joint Efficiency percent
Welded—Annealed					
80	L	94. 6	47. 5	32. 2	99. 5
−100	L	105. 8	54. 5	35. 7	100. 2
−200	L	114. 3	57. 9	35. 5	99. 8
−320	L	136. 6	69. 8	41. 0	102. 4
−423	L	160. 4	88. 5	36. 8	105. 5

See footnotes at end of table.

K-Monel—Continued

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Joint Efficiency, percent
		Welded—Pre-Aged			
80	L	99. 0	62. 7	8. 2	67
−100	L	109. 9	74. 9	8. 7	70
−200	L	118. 8	84. 9	8. 7	72
−320	L	133. 7	93. 2	9. 5	76
−423	L	158. 9	107. 9	10. 0	83
		Welded—Post-Aged			
80	L	152. 1	110. 1	19. 0	102. 8
−100	L	161. 5	120. 2	21. 2	103. 4
−200	L	165. 0	122. 1	20. 7	100. 1
−320	L	181. 6	134. 1	26. 0	102. 8
−423	L	197. 9	146. 1	24. 3	103. 1

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

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Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Joint Efficiency, percent
Base—Annealed					
80	L [a]	135	69	48	
	T [b]	135	66	48	
−100	L	173	108	38	
	T	175	109	37	
−200	L	187	122	37	
	T	187	121	37	
−320	L	184	104	56	
	T	184	102	56	
−423	L	207	122	49	
	T	207	115	48	
Base—Age Hardened					
80	L	199	147	16	
	T	190	137	20	
−100	L	201	152	14	
	T	205	162	14	
−200	L	210	167	12	
	T	220	173	13	
−320	L	229	179	12	
	T	223	179	10	
−423	L	239	199	9	
	T	229	198	9	
Welded—Annealed					
80	L	138	75	41	102
−100	L	155	86	42	90
−200	L	164	94	37	88
−320	L	189	115	41	103
−423	L	201	121	39	97
Welded—Pre-Aged					
80	L	154	115	6	77
−100	L	174	138	6	86
−200	L	179	144	5	81
−320	L	196	163	5	85
−423	L	205	171	6	85

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

Ti-6Al-4V

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
		Base			
75	L [a]	138. 9	133. 0	11. 0	1. 02
	T [b]	150. 9	145. 6	11. 3	
−100	L	161. 3	157. 9	9. 3	1. 00
	T	170. 4	169. 2	10. 0	
−200	L	178. 3	176. 7	6. 5	0. 99
	T	189. 6	188. 8	5. 2	
−320	L	218. 1	214. 0	13. 0	0. 82
	T	220. 5	218. 8	14. 8	
−423	L	239. 6	240. 4	1. 7	0. 61
	T	241. 9	240. 2	2. 0	
−450	L	242. 3	------	0. 2	0. 62
	T	------	------	------	
					Joint Efficiency, percent
		Welded			
75	L	138. 6	132. 9	7. 5	100
−100	L	159. 8	155. 4	6. 0	99
−200	L	178. 1	177. 1	5. 2	100
−320	L	220. 3	216. 8	7. 3	102
−423	L	229. 7	226. 6	2. 0	96
−450	L	241. 2	------	1. 0	100

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

Ti-5Al-2.5Sn

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base					
75	L [a]	134. 2	128. 1	12. 8	1. 20
	T [b]	134. 3	131. 2	14. 3	
−100	L	156. 9	151. 6	11. 8	1. 10
	T	157. 6	154. 9	11. 5	
−200	L	171. 8	169. 4	9. 3	1. 10
	T	175. 3	174. 0	10. 7	
−320	L	213. 1	207. 1	14. 0	0. 81
	T	213. 3	208. 3	13. 2	
−423	L	233. 8	233. 8	5. 0	0. 66
	T	243. 1	239. 2	6. 3	
−450	L	234. 6	------	1. 3	0. 62
	T	230. 6	------	1. 5	
					Joint Efficiency, percent
Welded					
75	L	137. 8	131. 2	11. 0	102
−100	L	157. 5	151. 9	10. 0	100
−200	L	172. 6	170. 5	7. 8	100
−320	L	215. 1	209. 5	10. 0	101
−423	L	243. 1	239. 2	6. 2	104
−450	L	236. 0	------	1. 5	100

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

Ti-13V-11Cr-3Al

Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
Base					
75	L[a]	137. 1	137. 1	13. 3	1. 20
	T[b]	140. 4	140. 4	12. 3	
−100	L	182. 1	181. 9	6. 0	1. 10
	T	184. 2	184. 2	5. 0	
−200	L	218. 0	215. 0	4. 5	0. 96
	T	219. 5	219. 0	4. 0	
−320	L	285. 3	282. 0	2. 5	0. 54
	T	286. 5	281. 6	2. 5	
−423	L	289. 2	------	0. 7	0. 40
	T	319. 6	------	0. 8	
−450	L	------	------	------	0. 39
	T	301. 1	------	0. 0	
					Joint Efficiency, percent
Welded					
75	L	144. 4	143. 9	10. 7	106
−100	L	193. 6	192. 7	4. 0	106
−200	L	232. 1	231. 6	2. 7	106
−320	L	170. 7	------	0. 0	60
−423	L	86. 7	------	0. 0	34
−450	L	129. 7	------	0. 5	43

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

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Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
			Base		
75	L[a]	23. 0	20. 4	36. 8	0. 95
	T[b]	22. 7	21. 4	29. 0	
−100	L	31. 9	22. 9	11. 2	0. 82
	T	30. 2	23. 4	9. 7	
−200	L	33. 7	23. 4	14. 3	0. 77
	T	32. 7	24. 9	12. 5	
−320	L	35. 6	25. 3	15. 5	0. 77
	T	33. 4	26. 9	13. 0	
−423	L	45. 9	35. 9	20. 5	0. 75
	T	42. 3	37. 9	10. 0	
−450	L	48. 3	41. 3	11. 5	------
	T	44. 2	40. 8	11. 0	
					Joint Efficiency, percent
			Welded		
75	L	23. 6	21. 5	6. 0	100
−320	L	30. 3	25. 7	9. 5	85
−423	L	40. 3	32. 8	3. 3	88

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

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Test Temperature, °F	Direction	Ultimate Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., percent	Notched-Unnotched Strength Ratio (K_t=10)
		Base			
75	L[a]	19. 7	18. 3	23. 7	1. 06
	T[b]	20. 5	19. 7	19. 0	
−100	L	28. 3	21. 4	10. 8	0. 94
	T	27. 8	23. 4	7. 8	
−200	L	29. 9	23. 5	13. 7	0. 94
	T	29. 5	25. 1	10. 7	
−320	L	33. 2	28. 1	13. 8	0. 95
	T	32. 9	30. 1	12. 3	
−423	L	42. 9	38. 8	14. 3	0. 86
	T	39. 4	38. 8	16. 5	
					Joint Efficiency, percent
		Welded			
75	L	18. 7	17. 9	17. 8	95
−100	L	24. 9	17. 9	8. 2	88
−200	L	26. 0	18. 8	8. 2	87
−320	L	28. 9	24. 6	8. 7	87
−423	L	41. 9	31. 2	3. 3	98

[a] Longitudinal to rolling direction.
[b] Transverse to rolling direction.

Appendix B—Approximate Change of State Temperatures of Several Common Substances

Substance	Temperature			
	Liquefying		Solidifying	
	°C	°F	°C	°F
Ammonia (NH_3)	−33. 4	−28. 1	−77. 7	−108. 0
Chlorine (Cl_2)	−34. 6	−30. 2	−103	−153. 5
Fluorine (F_2)	−188. 2	−306. 8	−219. 6	−363. 3
Helium (He)	−268. 9	−452. 0	−272. 9	−459. 0
Hydrogen (H_2)	−252. 8	−423. 0	−259. 1	−434. 0
Nitrogen (N_2)	−195. 8	−320. 4	−209. 9	−345. 5
Oxygen (O_2)	−183. 0	−297. 4	−218. 4	−361. 6

Note 1. All values for one atmospheric pressure.
Note 2. $°F = 1.8C + 32$.

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